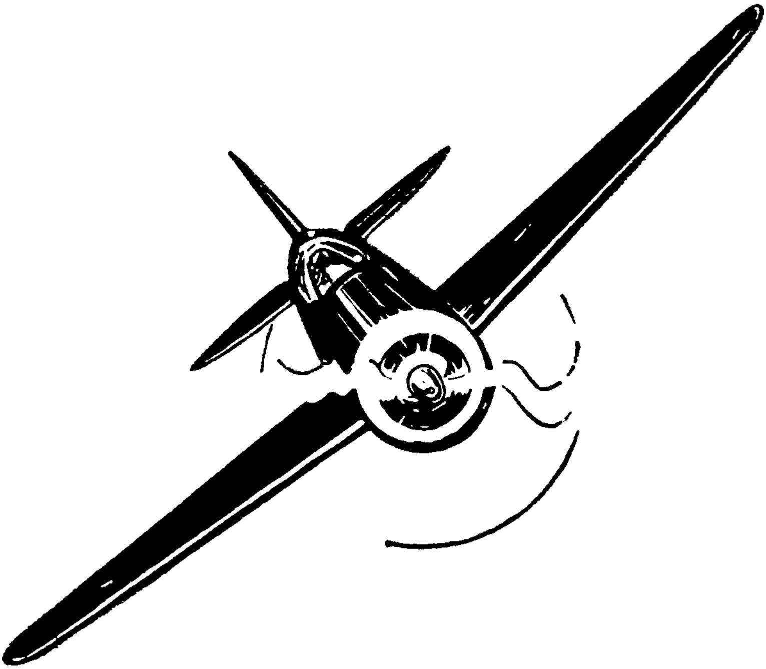

FIGHTER FACTS AND FALLACIES

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INTRODUCTION

Fighter Facts and Fallacies by John Lee comes at a time when it is most needed. Many of us are confused and discouraged by statements of self-styled experts, in the press and over the radio, as to the relative merits of various German, Jap, or British fighters and our own. It means nothing to say this one is "better" than that one, without mention of the particular superiority emphasized. It means still less, if no mention is made of the features sacrificed to attain this particular superiority, and the statement may be quite misleading.

Mr. Lee's discussion of the effects on performance of power, wing area, weight, and streamlining indicates how a designer thinks in juggling with his fundamental limitations. It also suggests what research men should be doing to lift some of these limitations. To get more power from the same weight and to reduce drag will pay large dividends in performance.

It is commonly assumed that tactical requirements determine the purpose of the design and hence the performance of the airplane. This may be true at a given time, but in the long run, new performance possibilities, made available by inventors, research men and designers, suggest new tactics. New tactical ideas lead naturally to changes in strategic thought. Some pre-war ideas about day bombing of distant cities were abandoned after the British interceptors showed what they could do to the Luftwaffe over England.

We may expect that the present limitations of the aeronautical art will be raised, as the results of research are applied in design, and that new types will appear and with them new tactics. Progress is continuous by refinements and improvements in current practice, but also new principles and inventions may suddenly become available. Such radical changes in the art as the constant speed propeller, high octane gasoline or cowled air-cooled engines, are unpredictable, but this country has in the past originated most of the important inventions.

I am glad Mr. Lee has undertaken to explain in his clear and concise way the fundamentals of airplane performance. He is the most competent man I know to do this.

JEROME C. HUNSAKER

Massachusetts Institute of Technology, Cambridge, Sept. 1, 1942

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PREFACE

In a sense, all military and naval airplanes may be considered as "fighter airplanes". In this book, however, the term "fighter" will be restricted to the pursuit airplane —the airplane whose primary business is to attack and destroy other aircraft. Much of what is said will also apply to bomber airplanes and to other types as well.

At the present time, when aircraft are of such vital importance in world affairs, and when military considerations change almost daily, it is extremely difficult to keep the fundamentals clear. They are in no way clarified by the published reports of military actions, which are necessarily incomplete, nor by the feature articles of popular writers who are often technically uninformed. Nor are they clarified by the reports of engineers, who seldom appreciate the difficulty which most persons experience in following a technical explanation.

To know one's fighters, their advantages and their weaknesses, and to evaluate the opposing fighters, is essential in any air endeavor. This is particularly true since it is necessary for fighters to be specialized. All of the best qualities cannot be incorporated in a single fighter, for superiority in any one respect requires design compromises which inevitably produce inferiority in most others.

One may build a fighter having long range and great fire-power and adaptability to a great variety of purposes, but one must be prepared to pay the penalty in poorer performance and poorer maneuverability. Likewise, one may sacrifice range and retain the fire-power and the performance; this is the familiar "interceptor" type, particularly useful in protecting small vital areas, like the island of Britain. Or one may sacrifice speed in favor of range and takeoff, which is the pattern for Naval carrier-based aircraft. Finally, one may sacrifice speed, range, and armor, retaining only maneuverability, which is the Japanese formula. But, whatever you do, "you cannot have your cake and eat it too".

To appreciate the relative importance of these compromises some general background is required. In the discussion which follows the point of view is that of the engineer, not that of the pilot or the tactician, who are specialists in their own right. Every effort has been made to visualize as clearly and simply as possible the fundamental aerodynamics of fighter aircraft.

I. THE EFFECT OF WING LOADING

A. SPEED AT SEA LEVEL

TWO FIGHTER AIRPLANES are compared, each carrying precisely the same load of fuel, pilot, armament, and accessories. Each has the same power, the same propeller efficiency, and basically the same drag. They differ in one fundamental, and one only. One has large wings and the other has small wings. Obviously, the smaller wings offer less resistance to the air than the larger wings. Hence, the airplane with the small wings has the definite military advantage of superior speed.

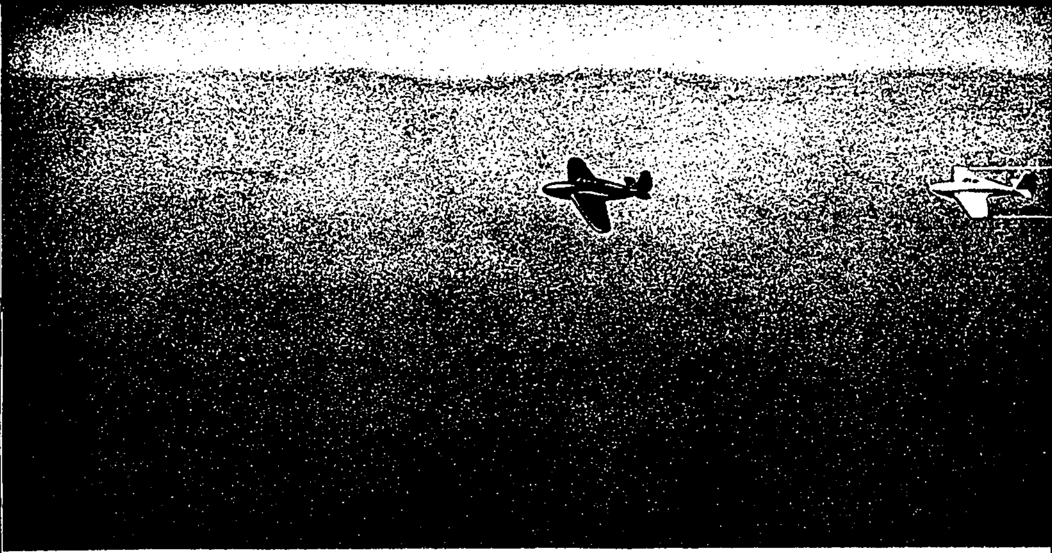
Actually, when the wing area is increased it is necessary also to increase the tail area, in order to provide adequate control for the larger wings. Both of these result in an increase in weight. However, the principal result of increasing the wing area is to reduce the "wing loading", which is defined as the total weight of the airplane divided by its wing area. The increase in airplane weight is relatively small and will be discussed later.

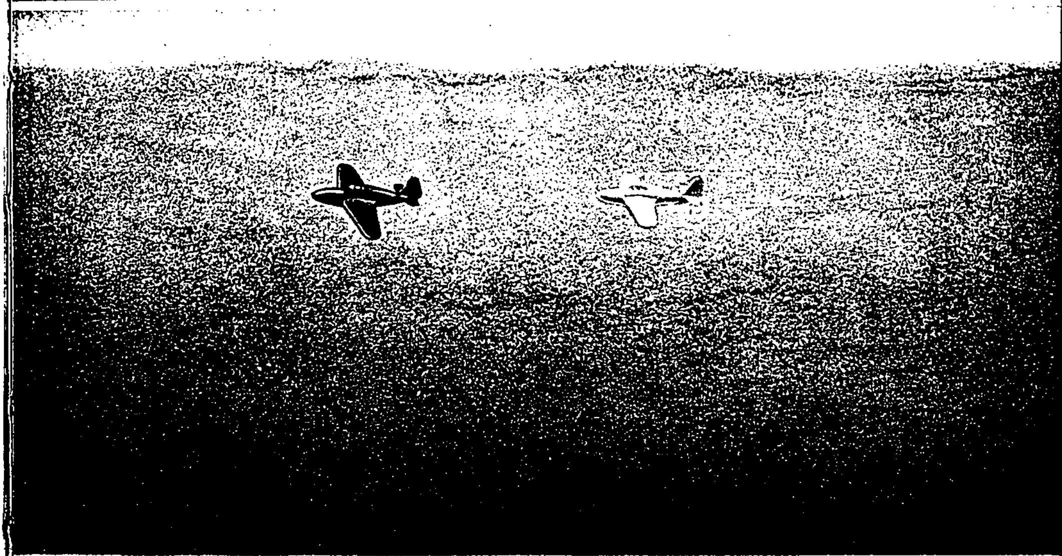
Although the airplane with the large wings (low wing loading) is the slower at sea level, it has been found to have compensating advantages. Particularly at altitude, it may actually be faster under extreme conditions than the airplane with small wings (high wing loading).

At low altitudes . .

the smaller plane with the higher wing loading . .

is faster and will also outclimb the larger plane



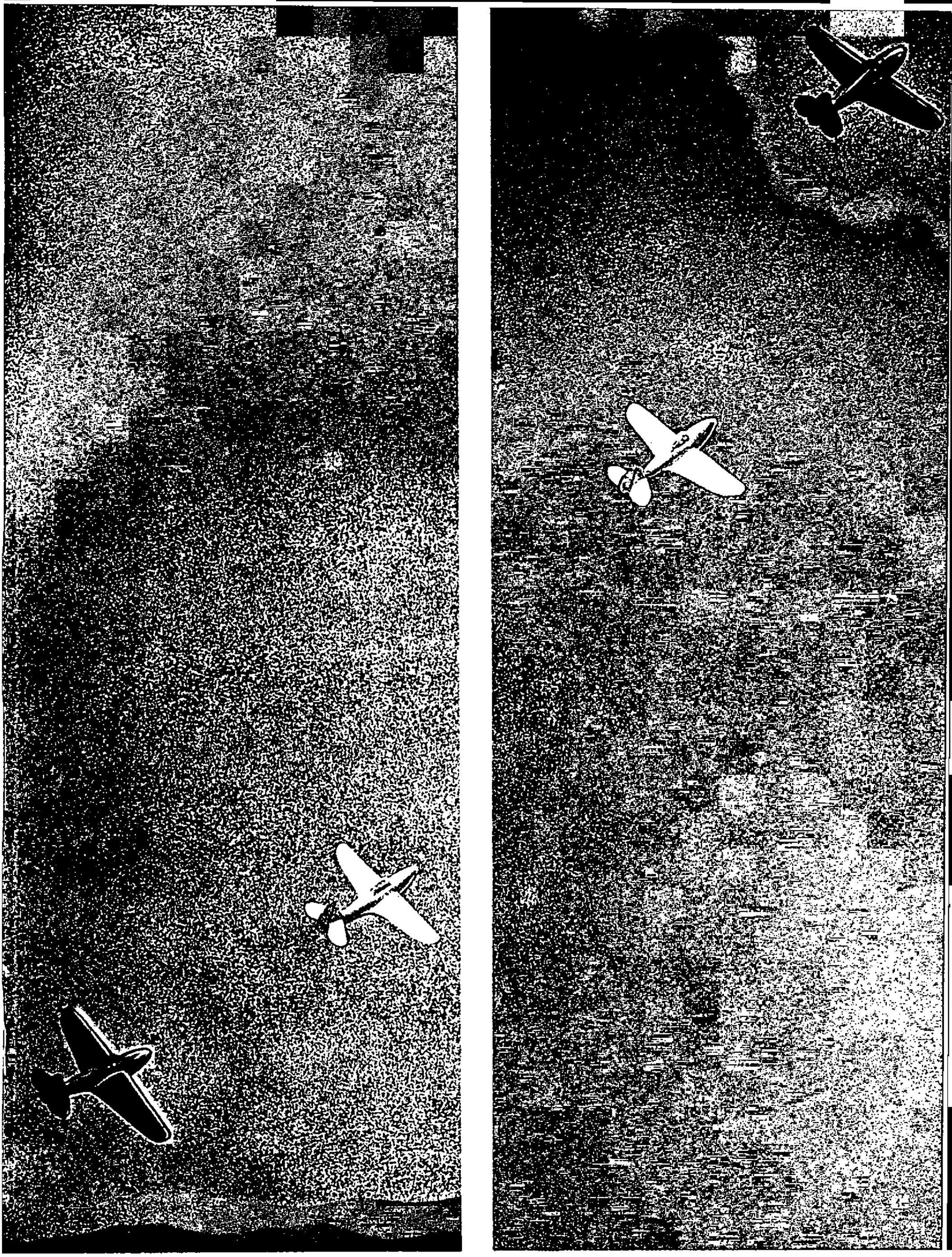


B. CLIMB

In the matter of climb, the airplane with the small wings and high wing loading will also have the advantage at sea level. The reason is the same, namely, the smaller wings have the smaller drag. On the other hand, it is probable that the *angle* of climb will favor the airplane with the low wing loading. It can climb more steeply, although not so fast. It has the advantage in a tight space.

As the airplanes climb to higher altitudes the situation changes. The air is less dense, and both airplanes must fly at a steeper angle of incidence to maintain the same lift upon their wings. Here the large wings are an advantage, for they do not have to fly at as steep an angle as the small wings which carry the same load. At this steeper angle the drags of the wings, tail and body are all increased, and under extreme altitude conditions the airplane with the small wings has much more drag than the airplane with the large wings. Thus, as ceiling is approached, the airplane with the low wing loading has the better climb and the faster high speed as well.

At some intermediate altitude the climb of the two airplanes is equal. The particular altitude is determined by the manner in which the wing area is changed. If the change in wing area is made by increasing the span of the wing while the chord, or width, is unchanged, considerable advantage in performance is obtained for the airplane with the low wing loading. If the change in area is made by increasing the chord, while the span remains unchanged, relatively small advantage is obtained for the airplane with the low wing loading. The explanation of this phenomena is given later, under the discussion of "span loading".



At the highest altitudes, the plane with the lower wing loading is faster and can outclimb the smaller plane

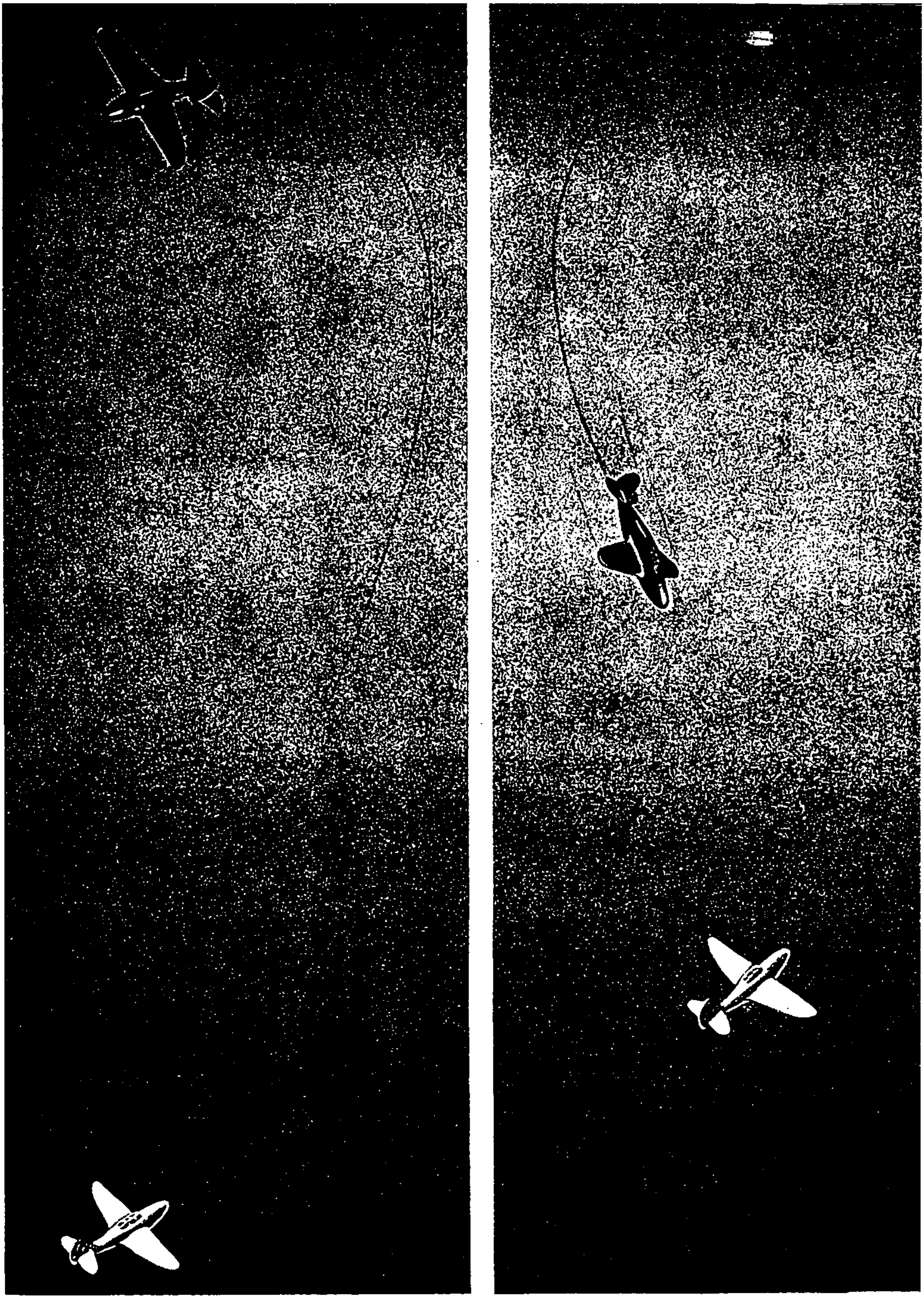
C. ALTITUDE PERFORMANCE

Of two otherwise identical airplanes, the one with the low wing loading will achieve the greater ceiling. This is because the larger wing area has a greater capacity to lift and therefore greater ability to handle the light air at high altitudes. It must be remembered, of course, that the airplanes which we are comparing have the same power and carry the same military load.

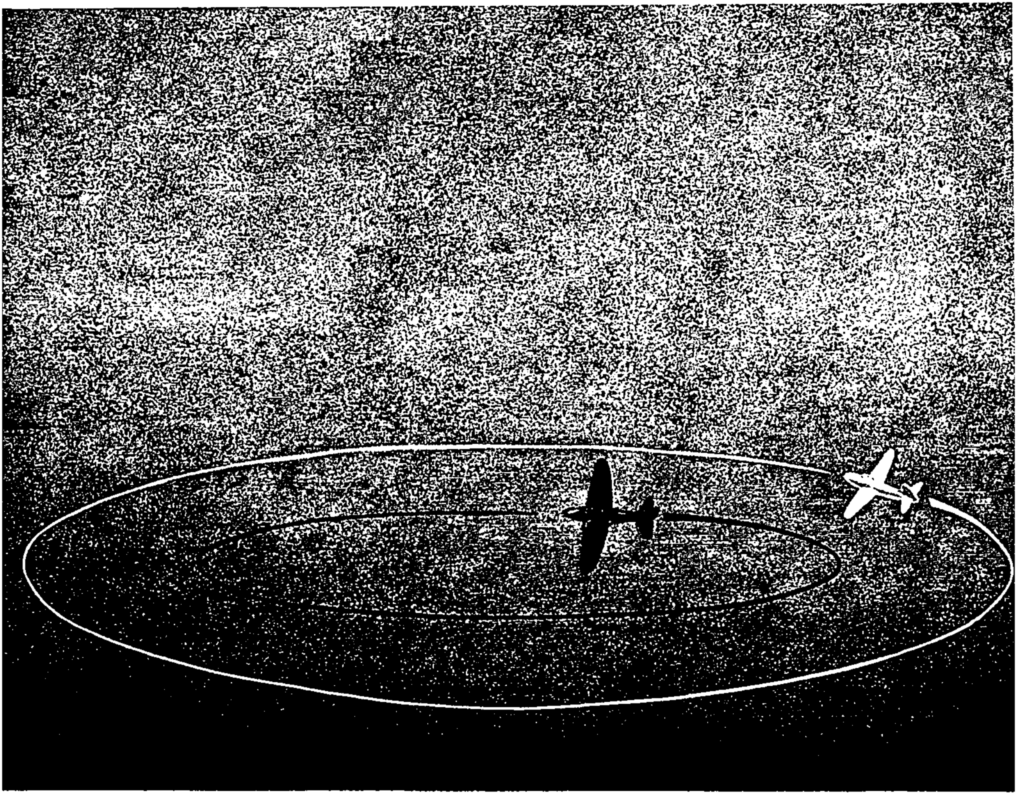
Having obtained the advantage of greater altitude, the airplane with the low wing loading can dive upon its highly loaded adversary, thus turning its altitude advantage into a speed advantage.

As previously mentioned, the airplane with the low wing loading is actually the faster as ceiling is approached. To be sure all fighting does not take place close to ceiling, but the advantages of altitude are sufficiently great that continuous effort is being made to increase the ceiling of fighter airplanes. Incidentally, at these extreme altitudes the pilot, even when breathing pure oxygen, may reach his ceiling before the airplane does, and hence some form of pressure cabin for the pilot may ultimately be required.

Another point to remember is that if an engagement takes place at high altitude the highly loaded airplane must be flown with much greater skill than the lightly loaded airplane. This is because there is only one flight angle at which an airplane can fly at its ceiling. The heavily loaded airplane is much closer to its ceiling than the lightly loaded airplane; hence the heavily loaded airplane has a more limited range of possible flight angles. Any deviation which the pilot may make from the optimum angle will result in losing altitude and, in many cases, in a complete stall or a spin.



With its superior altitude performance the lightly loaded plane can dive upon its more heavily loaded adversary

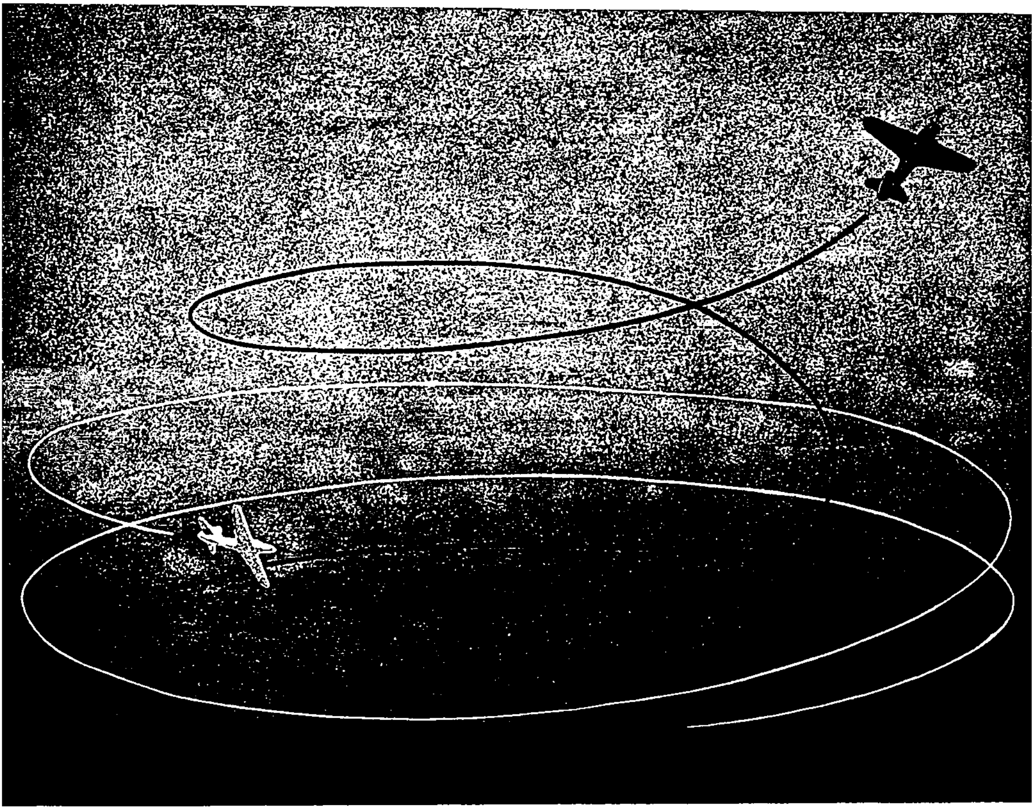


The superior maneuverability of the large-winged, lightly loaded

D. MANEUVERABILITY

This much misused term is often confused with the term "response". "Maneuverability" is the measure of the space required by an airplane to execute a given maneuver. "Response" is a measure of the rapidity with which an airplane follows movements of the pilot's controls.

The airplane with the large wings (light wing loading) will turn in a smaller circle than the airplane with the heavy wing loading. In other words, the airplane with the light wing loading is the more maneuverable. This is because the airplane with the larger wings can produce a larger lift to oppose the centrifugal force in a turn.



plane permits it to turn or climb "inside" the heavily loaded plane

The force which the pilot feels in a turn, and which causes him to "black out", is dependent upon two things; the radius of turn and the speed of flight. The smaller the radius or the greater the speed, the greater will be the force upon the pilot. Consequently, it is necessary to throttle down in a tight turn in order that the pilot can stand the high force which the airplane is able to impose. This in no way affects the *radius* of turn.

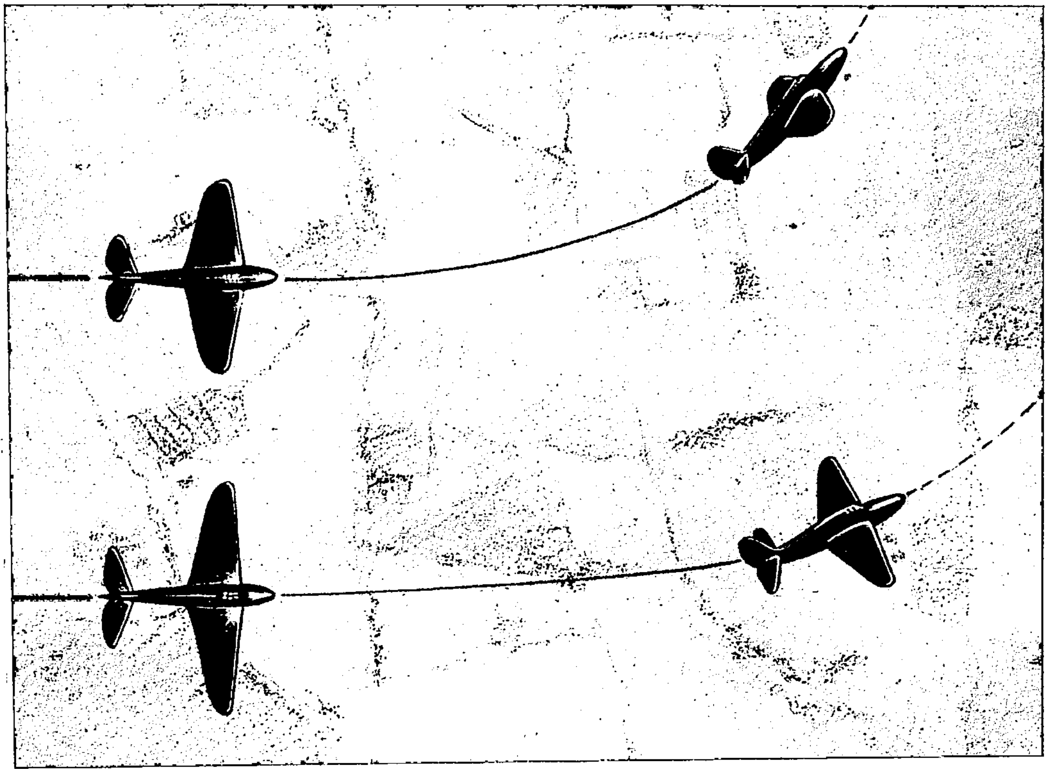
Except for the momentary dive, the plane with the large wings and low wing loading cannot be attacked by the more heavily loaded plane, which must circle outside of it. Furthermore, the plane with the large wings can change from circling to a steep spiral climb and continue upwards to the high altitudes, where its light wing loading gives it general superiority.

THE EFFECT OF WING LOADING

One other aspect of maneuverability is very important, the process of changing from straight flight to curved flight, or vice versa. This requires that the airplane be rolled to assume the proper angle of bank. The greater the wing span, the more the airplane resists rolling, and the greater will be the time required to get the airplane into or out of a turn. Hence the small airplane with the short span has an advantage in this respect.

The difficulties are further complicated by the tendency of the forces on the pilot's control stick to become exceedingly heavy at high speeds, even though the controls are balanced to the practical limit. This problem of designing lateral controls which will easily roll a large airplane at high speed is one of the most difficult problems with which designers are faced.

The shorter the span, the quicker the bank



E. TAKEOFF AND LANDING

The lower the wing loading, the slower will be the landing speed, because a large wing area produces a greater lift and hence can sustain the airplane at a slower speed than does a small area. Similarly, the lower the wing loading, the shorter will be the takeoff, since the length of the takeoff run depends largely upon the minimum speed required to support the airplane, and it takes less distance to accelerate to a slower speed.

A few figures may be of interest. If the wing loading is increased from 35 to 50 pounds per square foot, all other factors remaining equal, the landing speed might increase from 75 to 90 miles per hour. Furthermore, if the pilot should be involved in a crash landing the force acting upon the pilot in the crash would be nearly 50% greater at 90 miles an hour than at 75. This increase in wing loading would also increase the takeoff run some 35%.

Practically all airplanes are fitted with auxiliary high-lift devices, usually in the form of hinged wing flaps of some type. All of these devices will cause the wings to produce considerably higher lift than normal at the expense of considerably higher drag. The increased drag is of great advantage in landing, since it slows the airplane down and permits it to approach the ground at a steep angle without gaining excessive speed. In this manner airplanes with high-lift devices can make steep approaches over an obstacle and get into a relatively small field, while airplanes without these devices tend to "float" indefinitely and are extremely hard to get into a small field.

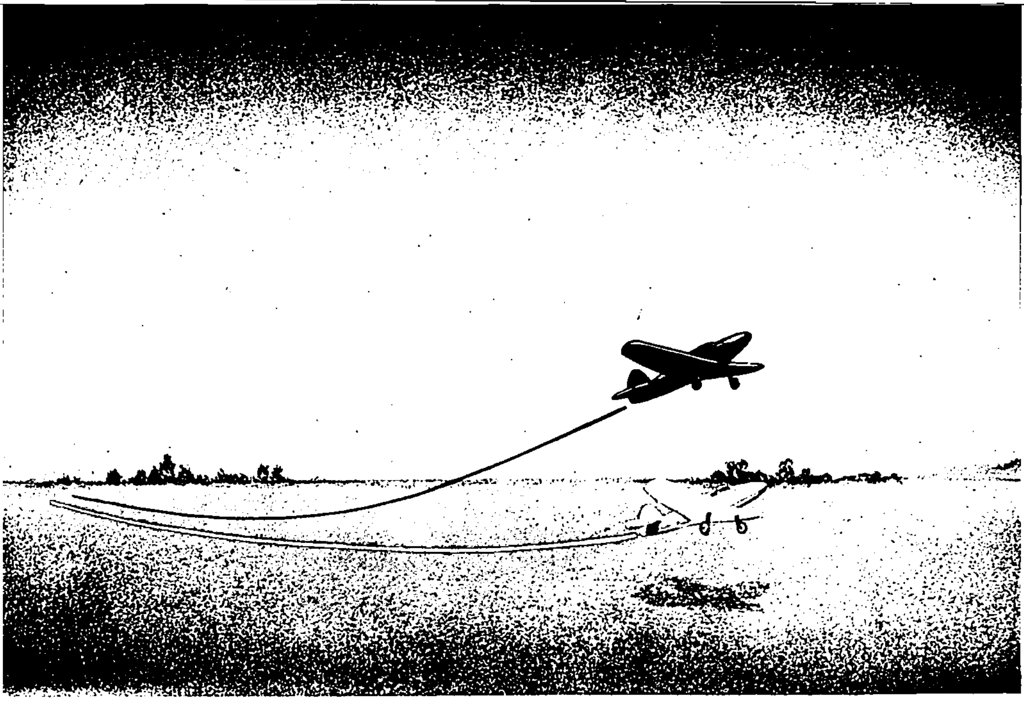
The increased drag of high-lift devices is a definite disadvantage during takeoff, where the increased drag prolongs the takeoff run. Hence, the shortest takeoffs are usually accomplished with the high-lift flaps depressed only a small amount, if at all.

The same difficulty arises when the high-lift devices are used in combat maneuvers. Even if the flaps and wings were made strong enough, which they usually are not, the enormous increase in drag tends to ruin the airplane's performance.

Another of the current research problems is to design a high-lift device which will not increase the drag in combat nor impose an additional control upon the pilot. If such a device could be developed, airplanes with high wing loading and high speed might also obtain some of the advantages now inherent in airplanes having low wing loading.

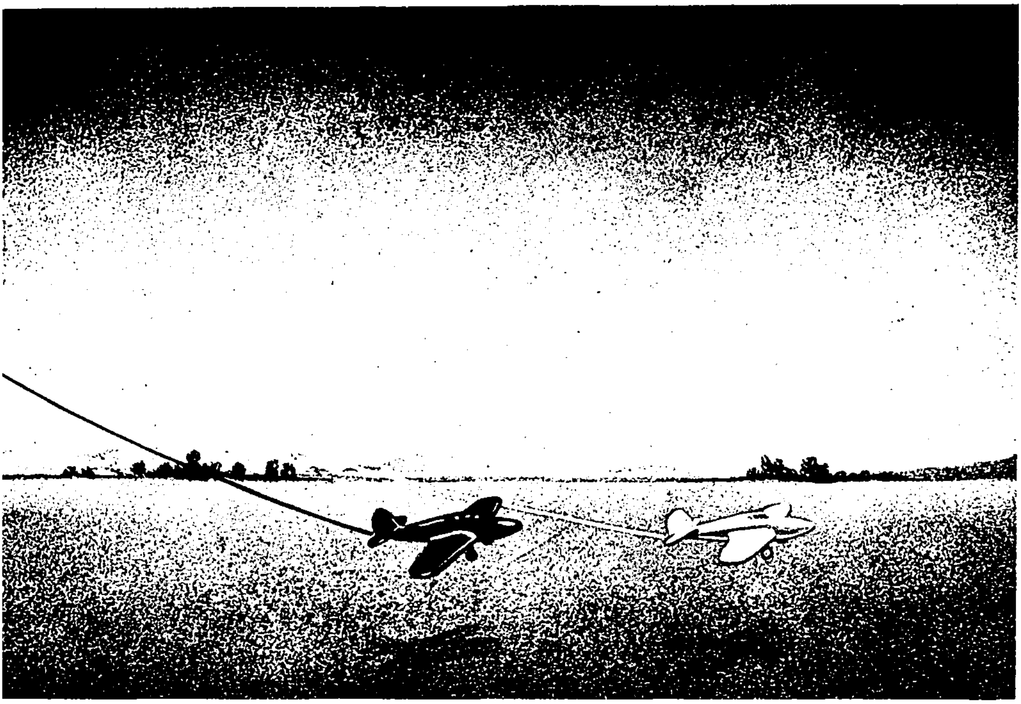
The astonishingly large effect of wind on takeoff is interesting. Take, for example, a pursuit airplane which leaves the ground at 90 miles per hour after a 500-foot run in still air. If the airplane were headed into a 30 mile per hour wind, its takeoff would be cut to about 250 feet. If the wing loading were reduced so that the airplane left the ground at 80 miles per hour, the takeoff would be cut to approximately 400 feet in still air, or 170 feet against a 30 mile per hour wind. Thirty mile per hour winds are rare on land, but they can readily be attained on aircraft carriers, where the effective wind is the sum of the actual wind and speed of the ship.

The need for short takeoffs from carriers or from battleship catapults explains the general tendency for Navy fighters to have lower wing loading than Army fighters. Although this lower wing loading may adversely affect the speed and climb at sea level, as we have seen, it has compensating advantages in improved maneuverability and altitude performance.



The lower the wing loading, the shorter the takeoff . . .

. . . and the lower the landing speed



II. THE EFFECT OF POWER LOADING

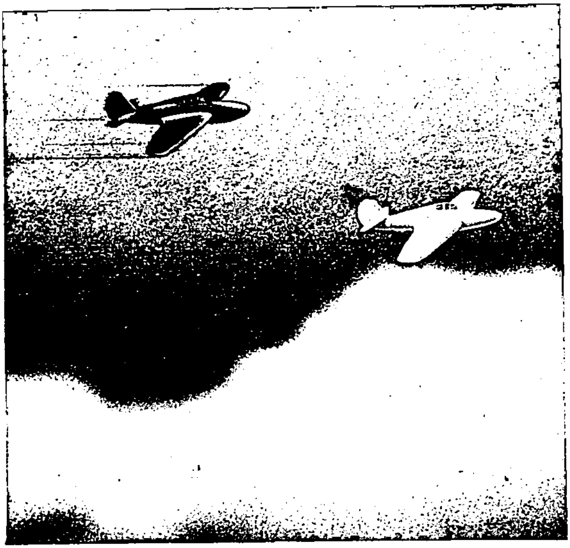
A. SPEED

If two fighters are identical except for power, the more powerful will be the faster. This is true at all altitudes and under all conditions. The benefits of superior power can be reduced, of course, by poor streamlining, excess weight, and bad design. But, other things being equal, there is no substitute for power.

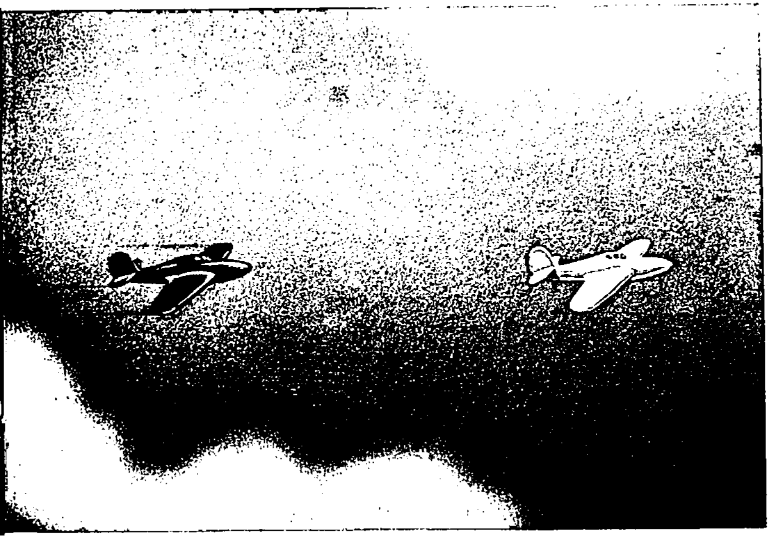
Superior power need not entail any penalties. Maneuverability need not be reduced; handling qualities need not be sacrificed. So long as the two planes have equal wing loading and equal streamlining, the one with the lower power loading (lower weight per horsepower) will have the greater speed.

Sometimes we hear of high powered planes being less maneuverable. This is usually the result of installing a more powerful, but heavier, engine. The increased weight of the larger engine, with its larger fuel supply, will increase the wing loading, and the increased wing loading, not the increased power, will reduce the maneuverability.

To get the whole benefit of superior power, without penalty, the wing loading must remain the same. If the superior power



At all altitudes the airplane with the lower power loading will out-perform its adversary



results in a heavier power plant, then a larger airplane is required, or alternately, some of the military load must be omitted.

Increased power does not always mean increased weight. For example, it is sometimes possible to improve the engine output by skillful design or careful development so that substantially more power is available with a negligible increase in weight.

When this can be done without sacrifice of reliability or without disrupting war-time production, it often pays big dividends in performance.

Another instance of increased power without increased weight is the substitution of an air-cooled power plant for a liquid-cooled power plant. Since the air-cooled installations are lighter per horsepower, a more powerful air-cooled power plant can be installed for the same weight. The change in drag, if any, is small and will be discussed later. However, drag is relatively unimportant during takeoff and climb, in which case the increased power is pure gain.

Several attempts have been made to obtain a momentary boost in power without increasing the weight. This can be done at sea level by opening the throttle beyond the usual stop, and thus making use of the excess supercharging which is available at low altitudes. The "military" or "takeoff" rating of an engine which permits operation at high power for limited time only, is an example of this sort. Such over-rating cannot be carried too far, even for brief periods, without the use of some special fuel or agent to prevent "knocking" of the engine.

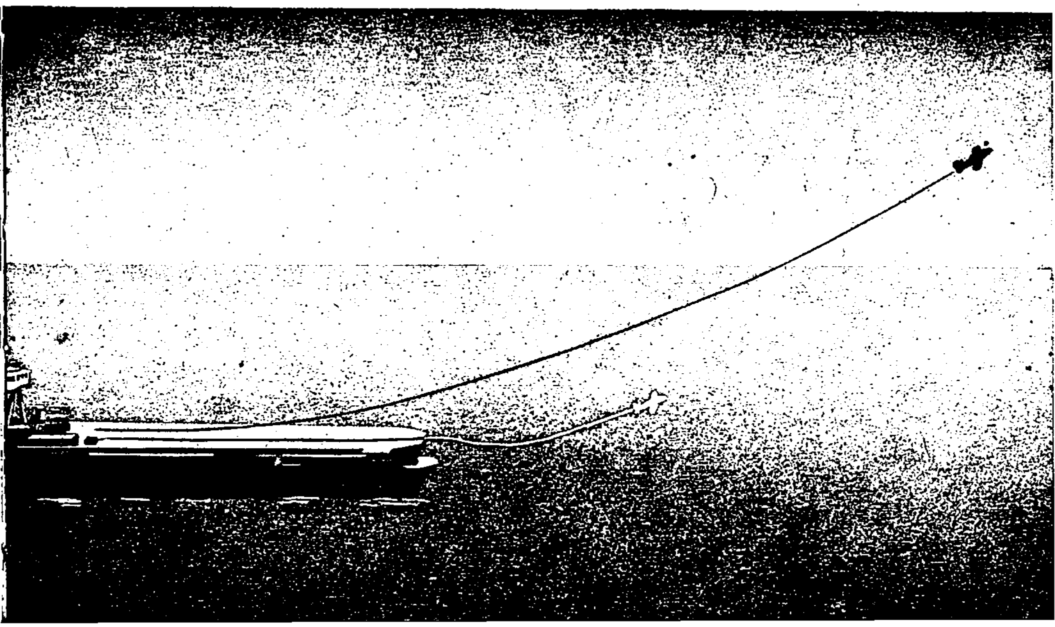
At altitude, however, there is no excess supercharging. Momentary boost can theoretically be obtained at altitude by discharging high pressure oxygen and fuel from a special container into the engine. Such expedients cannot be used often, for they impose greater loads upon the engine than it is designed to take. Some engineers feel that these expedients should never be employed, on the grounds that the momentary boost in power is worthless if the engine is abused and may "let you down" later.

B. TAKEOFF

The advantages of low power loading are particularly clear in takeoff. The lower the power loading the less weight must be accelerated by each horsepower and consequently the shorter will be the distance required to get this weight up to flying speed. It is not a question of how much power the engine has. It is a question of how many pounds each horsepower must accelerate.

One confusing thing about takeoff is the effect of the propeller. Propellers may be designed primarily for speed or primarily for takeoff conditions. Thus, even though the power loading may be extremely low, the takeoff may be poor if the propeller has been designed for high speed conditions. For this reason, if for no other, the casual comparison of airplane performances may lead to wrong conclusions.

Low power loading means good takeoff



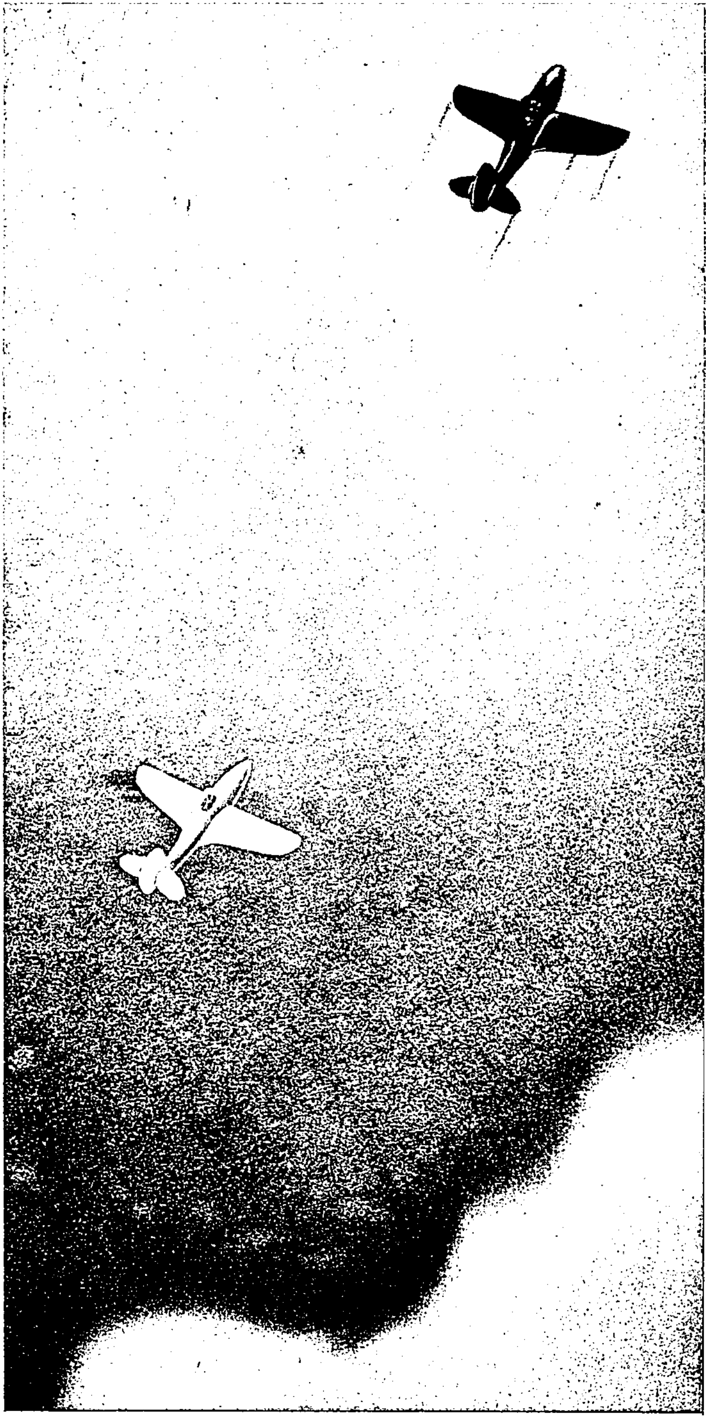
C. CLIMB

Superior power means superior climb, as well as superior speed. In fact, if the wing loading and streamlining are the same, the airplane with the greater power (lighter power loading) will outperform in every way—takeoff, climb, speed, and ceiling. There is no substitute for power!

Increased power means more than just a bigger engine. It also means a bigger propeller, heavier fuel load (or less range), larger oil-cooler, and many other increases. This explains why the fighter of today is so much larger than the pursuit plane of the last war, and why the more powerful fighters yet to come will be larger still. The increased size and weight are undesirable, but the great gains due to increased power more than make up.

Since the larger and more powerful airplane is capable of carrying a heavier military load, that greater load will inevitably be added, and once again there is a demand for more power. We are thus confronted with a strong tendency to continually increase the power and the size of fighter airplanes. As in other fields of development, many engineers have suggested starting all over again. Why not build a really little airplane with the same power loading and wing loading as the large plane?

This can be done, but it entails sacrifice. A little airplane cannot carry as much as a big one and give the same performance. But if the airplane's mission is simplified or specialized, and its load thereby reduced, the smaller fighter becomes a practical possibility. One of the major problems is to determine at which point this simplification and reduction of size is justified.



At any altitude there is no substitute for power

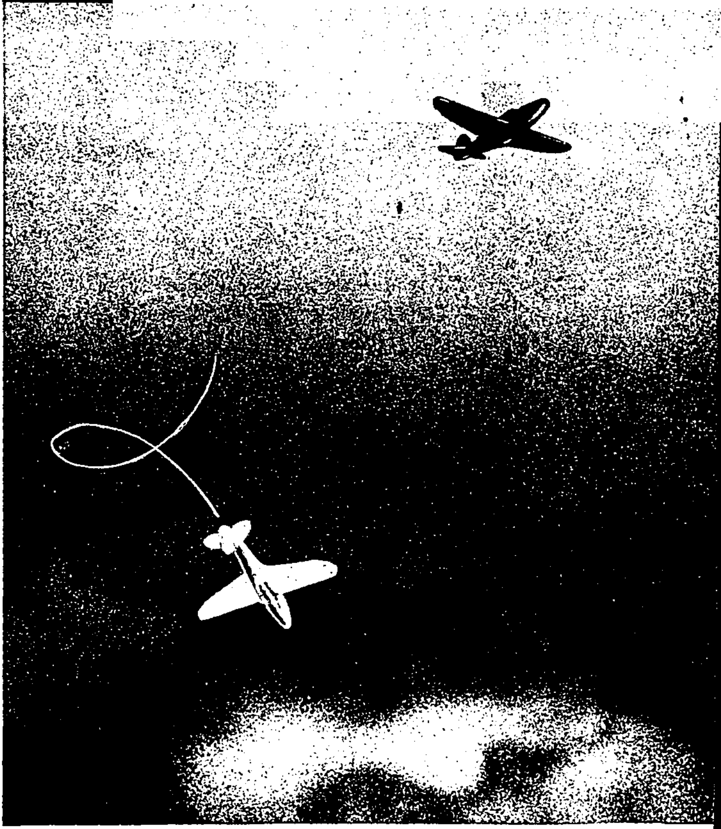
D. SUPERCHARGER PROBLEMS

The most effective way to improve the power loading at altitude is by means of the supercharger. At higher altitudes, where the air is less dense, the engine power falls off rapidly, so that the gain in power which can be accomplished by increased supercharging greatly overbalances the increased weight and complication of the supercharger. All high-power aircraft engines incorporate a built-in gear-driven blower, or supercharger, of moderate capacity.

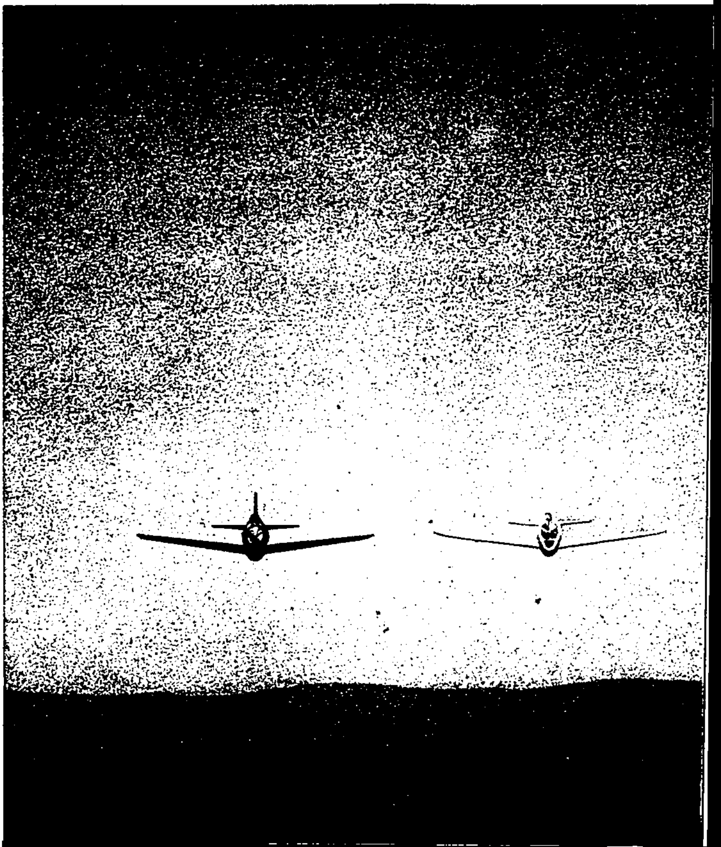
The built-in supercharger will "boost" an engine to maintain sea-level air pressure to some given altitude, usually called the "rated altitude" of the engine. Roughly speaking, the engine will produce the same power at this altitude as at sea level. Some confusion exists, however, because of the fact that many engines are given a special "takeoff rating", above their normal sea level capacity. This is one form of the temporary boost, previously discussed, and is only permitted for a limited time. The "takeoff rating" is obtained, of course, by opening the throttle past the normal stop and permitting the supercharger to supply excess pressure at low altitude.

Another confusing fact is that any supercharger which will carry a given engine power to a specified altitude will carry a lower power to a higher altitude. By custom, engine manufacturers, when improving an engine or a supercharger, will sometimes increase its "rated altitude" not only by the amount of the legitimate improvement, but by a greater amount as well, and will make a compensating reduction in the rated power at the new altitude. In this discussion, when we speak of an increase in"rated altitude" we shall define it, for simplicity, as the increase in altitude at which the *same engine power* can be obtained.

When air is compressed it becomes heated, a fact familiar to anyone who has operated a hand tire pump. Since the super-



At altitude the supercharged airplane is superior in all ways

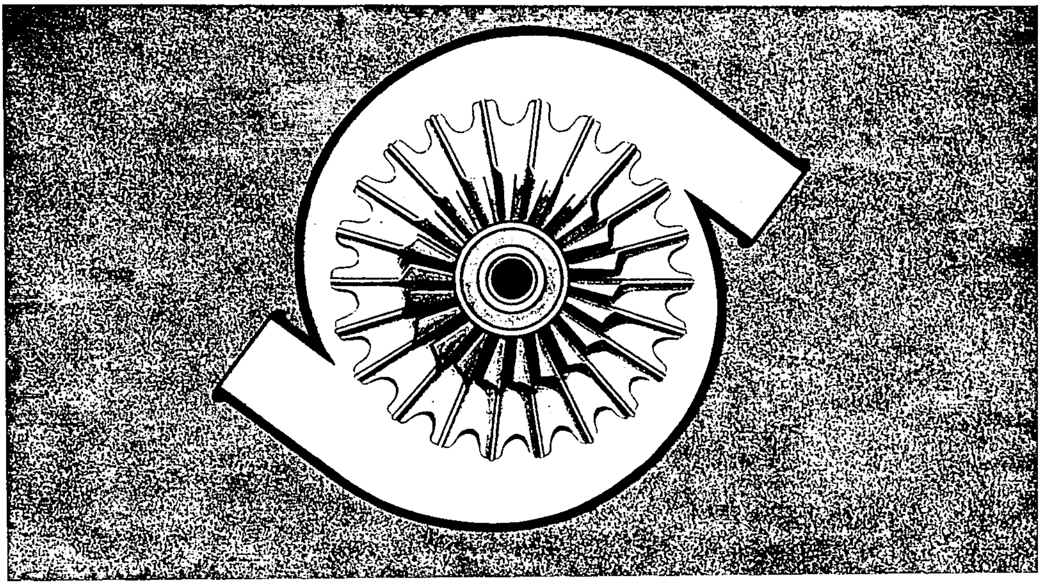


At sea level the unsupercharged airplane is slightly better

charger is essentially a pump, the supercharged air tends to become so hot that the engine will knock. Consequently, the most highly supercharged airplanes are equipped with "intercoolers" to cool the air before it passes to the engine. These intercoolers are necessarily large, for the air must pass through them relatively slowly to avoid losses. In spite of the weight and drag which they contribute, they more than pay their way in the increased engine output which they permit.

This heating of the air by a supercharger takes place even if the supercharger is 100% efficient. Usually superchargers are only about 65% efficient; that is, they usefully employ only about 65% of the power going into them. The remaining 35% is transferred directly into heat. This requires much larger intercoolers than would otherwise be necessary, with their attendant penalties in weight, drag, and bulk. Improved supercharger efficiency will therefore pay for itself twice over.

An efficient supercharger pays double



E. SUPERCHARGING METHODS

The supercharger is essentially an air compressor. Practically all aircraft engines use the centrifugal type of supercharger, because its high speed of rotation permits it to compress large volumes of air with a minimum of size and weight. However, there is a definite limit to the pressure which a single supercharger will produce. Hence, supercharging at high altitudes is always accomplished in two or more stages.

There are two well-established methods of supercharging: the mechanically-driven supercharger which is integral with the engine, usually called a "two-stage"; and the exhaust-turbine-driven type, usually called a "turbo-supercharger" or merely a "turbo". Actually, both are two-stage machines, one stage being always mechanically driven by the engine and the second stage being driven either independently by the turbine, or mechanically by the engine. Possibly three-stage units may be required in the future for the very high altitudes. The third stage, like the second, may be driven by the turbine, or all three may be driven mechanically by the engine.

It might be well to mention the "two-speed" supercharger while we are defining terms. This is any supercharger which incorporates a gear shift device which permits it to be driven at either of two speeds; fast for higher altitudes where it is needed, and slow for lower altitudes where the need is less and it consumes excessive power. The two-speed mechanism (or its equivalent in the form of a fluid-coupling) is frequently employed on either the single-stage or the two-stage supercharger.

It is controversial which type is superior, the "turbo" or the mechanically-driven supercharger. In the case of the "turbo", sufficient back pressure is maintained in the exhaust system so that sea-level conditions exist at the exhaust port, irrespective of the altitude. Hence, we may argue that no power is taken from the engine to drive the supercharger. In the case of the mechanically-driven supercharger, power is obviously taken from the engine shaft to drive the supercharger. However, in a mechanically supercharged engine, the pressure in the exhaust system is less at altitude than at sea level because the air pressure is less at altitude. This reduction in pressure outside the engine cylinder is the direct equivalent of increasing the pressure inside the cylinder. Either one adds to the power of the engine. Thus some power is added to the mechanically supercharged engine which partially offsets the power required to drive the supercharger.

There is another effect, not so well understood, which contributes to the power of an airplane, and that is the thrust from the engine exhaust. This force, which is the equivalent of the "kick" from a rifle, is independent of the speed of the airplane. However, the power which this "kick" produces will increase directly with the airplane speed (because power is the product of force times speed) and may amount to 10% of the total propelling force at top speed. The most effective type of exhaust thrust jets are those which are fitted to each individual cylinder, and these can only be fitted to the mechanically-supercharged engine.

The "two-stage" with jets and the "turbo" are both effective. Both are still in the development stage; both have problems of flame suppression for night fighting. Although the present tendency is to use the "turbo" for extreme altitudes and mechanically-driven superchargers for medium altitudes, experience is not yet sufficient to determine which type will ultimately be found best for any given type of service.

Supercharging is the most effective means of increasing power, or reducing power loading, at altitude, and thereby obtaining the benefits of speed and the tactical advantage which altitude provides.

The "Turbo" and the "Two-Stage" are both effective

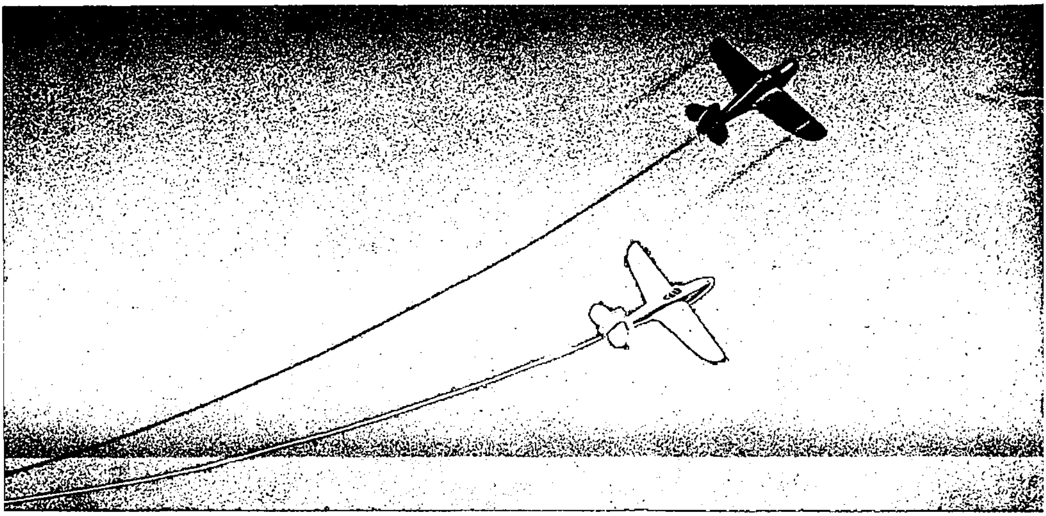
III. THE EFFECT OF WEIGHT INCREASE

A. USELESS WEIGHT

An airplane always gets heavier in service. Not only are new "gadgets" added to it in the field, but each new model invariably contains additions and improvements. These improvements, particularly when they are made during emergency conditions, are apt to be unnecessarily heavy.

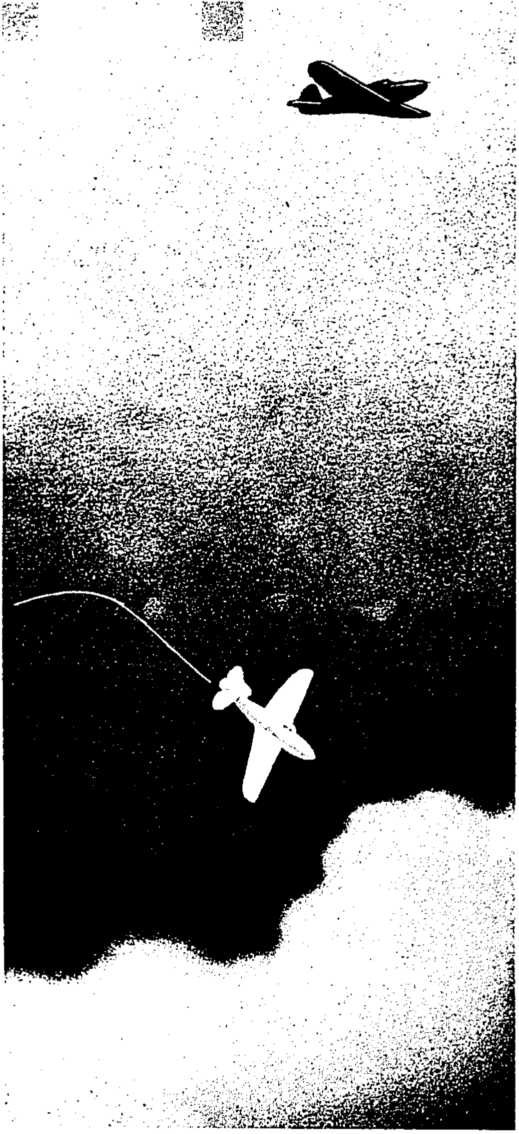
The increase in weight from one model airplane to the next, supposedly similar, model is often alarming. A figure of 10% weight increase per year is occasionally quoted by engineers. Adding weight increases the wing loading and the power loading at the same time. We have already seen the effects of increased wing loading and power loading separately. Together they are much more serious. Adding weight has but little effect on the high speed of an airplane except near ceiling, where it is definitely harmful. However, adding weight seriously affects takeoff and climb and ceiling, as well as maneuverability.

Of course, weight increase is often necessary as a result of service experience. It is essential that parts which are found to be weak or unsatisfactory be improved. It is obvious that main-



Added weight ruins takeoff . . .

. . . and Climb

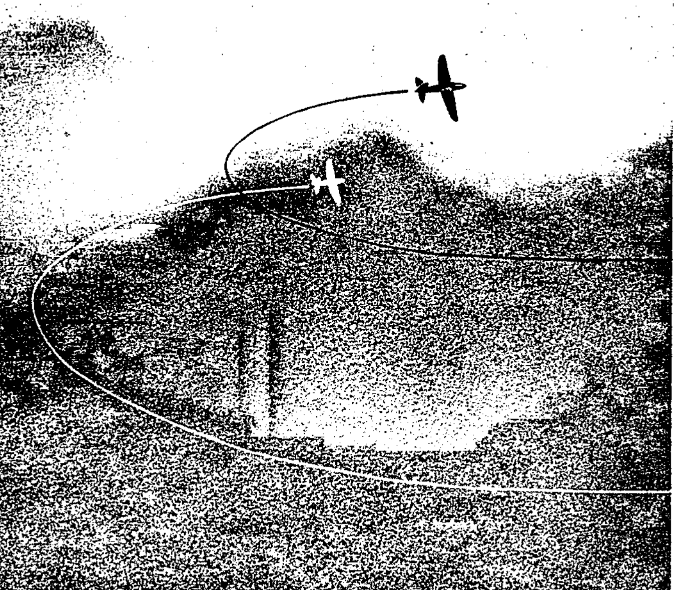


. . . and Ceiling

tenance must be made reasonably convenient, or it cannot be adequately done. Improved serviceability and convenience mean increased weight. But not all weight increases requested by service personnel are legitimate. Many are requested without realization of the harm which increased weight can do.

So important is the reduction of unnecessary weight that practically all aircraft designers set up a weight "bogey" when a new design is started. Any part, even a small detail, which exceeds the estimated "bogey" is redesigned. Herein lies the source of much controversy between the engineer, who seeks primarily to make the detail parts light, and the shop personnel, who seek primarily to make them easy to produce.

However, the rigid adherence to the policy of keeping the weight below "bogey", although it means much grief to the designer and great production obstacles to the shop, makes the difference between the best fighter and the second-best. A second-best fighter, like a second-best poker hand, is a very bad bet.



Added weight spoils maneuverability

B. WEIGHT AND SIZE

It is a fundamental law of nature that when an object is increased in size its weight increases faster than its surface area. A handy rule of thumb is that if the area is increased 2% the weight will be increased 3%.

Thus it follows that if we build a large airplane precisely similar to a small airplane the structural weight of the large airplane will increase more than did the wing area. Carrying this to the extreme, it would appear that if an airplane were built large enough it could not carry its own weight, let alone any useful load. This argument has been used since the time of the Wright brothers to prove that there is a practical limit to the size of an airplane.

Such reasoning overlooks one essential point. The law that weight increases more rapidly than size applies only to *similar* objects. Airplane designers have evaded this law by changing the form of their structure to a more complicated and more efficient type as the size of the airplane increases.

The fact that we have evaded the law so far does not mean that the law does not exist. It makes itself felt in two important ways. You cannot "scale up" a large transport airplane, for example, into a giant cargo plane without a serious weight increase. The two planes may appear identical on the outside, but to avoid the weight penalty, the internal structure of the larger plane must be much more carefully worked out. Hence the development of new types of very large aircraft is a much longer and more difficult process than most inexperienced people appreciate.

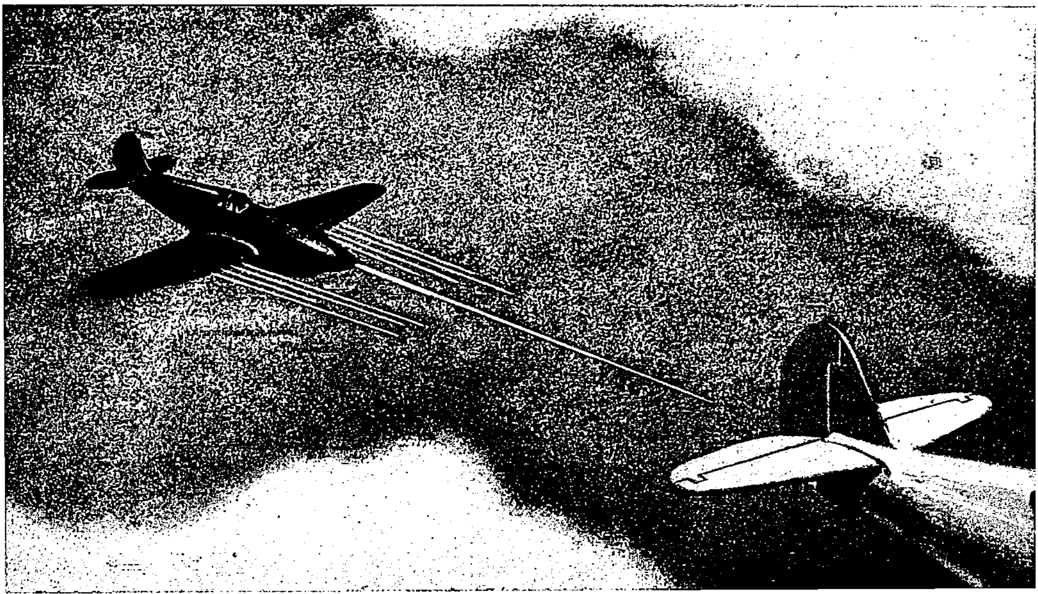
In the small fighter airplanes the weight law makes itself felt in requiring greater structural complexity as the size of the airplane increases, and this involves more difficult manufacturing and greater expense.

C. ESSENTIAL WEIGHT

The most frequent reason why weight is added to a fighter airplane is to increase the military load. This weight may take the form of more guns, more ammunition, more bombs, more armor, more incidental equipment, or more fuel. It will also take the form of more structure to support the increased military load. Whatever form it takes, it harms the performance and it reduces the maneuverability.

The advantages of specialization now become apparent, and possibly need some emphasis. To repeat verbatim a few sentences from the Preface, one may build a fighter having long range and great fire power and adaptability to a great variety of purposes, but one must be prepared to pay the penalty in poorer performance and poorer maneuverability. Likewise.

Greater fire-power means greater weight



one may sacrifice range and retain the fire-power and the performance; this is the familiar "interceptor" type. Or one may sacrifice speed in favor of range and takeoff, which is the pattern for Naval carrier-based aircraft. Finally, one may sacrifice speed, range, and armor, retaining only maneuverability, which is the Japanese formula. But, whatever you do, "you cannot have your cake and eat it too."

Many expedients have been tried to obtain the tactical advantages of long range and great striking power without paying the penalty in performance. This explains the interest in assisted takeoff, in refuelling in flight, in towed gliders, and in disposable auxiliary fuel tanks. At best, these are only expedients. However, if one is attacking from a great distance and the enemy is near his own base, some sort of expedient is necessary. Otherwise, one will be the second-best fighter when the fight takes place.

Longer range means greater weight

The clean airplane is the fast airplane . . .

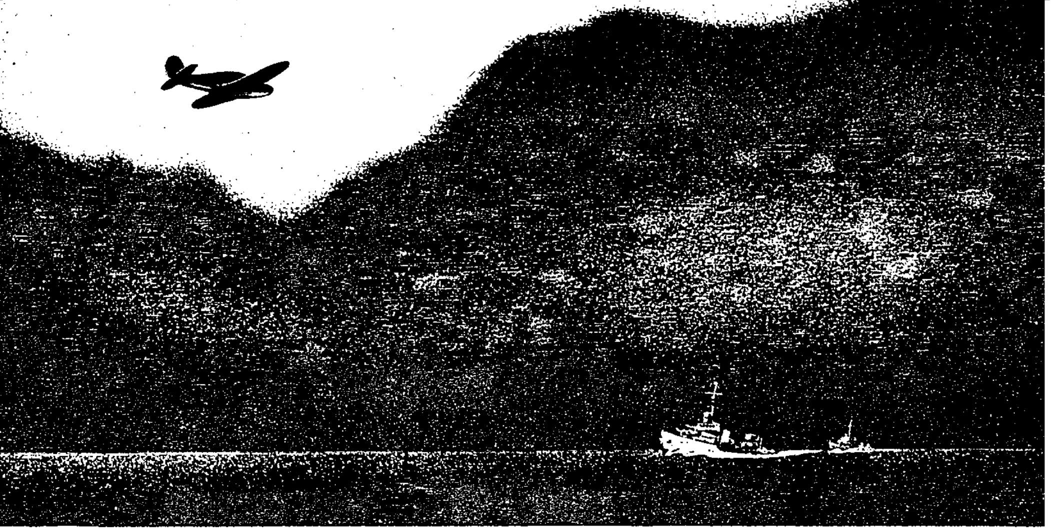
IV. THE EFFECT OF STREAMLINING

A. THE CLEAN AIRPLANE

THE WORD "streamline" is one of the most used words in aviation and perhaps one of the least understood. In the usual sense, a well "streamlined" airplane is one which offers the minimum resistance considering its size.

Taking two airplanes of equal power, weight, and size, the well "streamlined", or clean airplane, will be the faster. This is obvious. That the clean airplane will also have the longer range is less obvious. If the drag of a long range fighter is low, then the fighter can cruise at a faster speed for the same power, or at the same speed for less power. In either case, the result is increased miles per gallon, which is increased range.

However, improved streamlining has practically no effect upon the climb of the airplane. This is because of an additional



. . . and the long range airplane

. . . but it doesn't climb much better

drag known as "Induced Drag", which will be discussed later under "The Effect of Span-Loading". Although unimportant at high speed, induced drag becomes extremely important in a climb. The induced drag is in no way dependent upon the cleanness of the airplane. However, it is so great a proportion of the total drag in a climb that the cleanness of the airplane makes proportionally little difference. Furthermore, climbing is usually done at low flying speeds where the difference in drag between the "clean" airplane and the "dirty" airplane is relatively small.

A distinction should be drawn between the airplane which is clean because it is well streamlined and the airplane which is clean because there is little on it which requires streamlining. No matter how skillfully streamlined a radio mast may be, for example, it still has more drag than if it were omitted entirely. Whenever practical, cleanness should be attained by elimination, rather than by streamlining.

The importance of the drag of small objects cannot be overemphasized, nor can their interference with the air flow over large objects. In the latter case, the drag of the large object may be increased several fold. The fact that the biplane fighter of the last war contained a considerable number of these small objects, such as struts and wires, which could not be readily eliminated, was one of the powerful factors which finally rendered the biplane fighter obsolete.

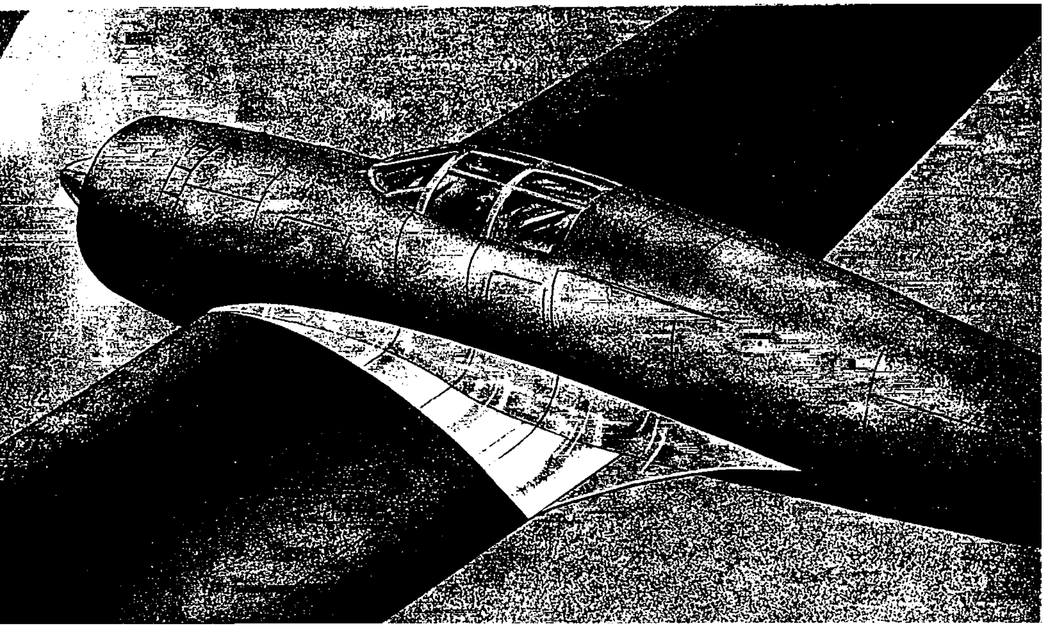
One other characteristic of the clean airplane is worth noting; since it has little air resistance considering its size, it tends to "float". Were it not for landing flaps and brakes it would be extremely difficult to get a clean airplane down into a small field.

B. STREAMLINING IS TRICKY

When two well streamlined objects join each other, the result may still be very poor streamlining, because each object may adversely affect the other. In the sketch below, the presence of the rounded fuselage interferes with the normal flow over the top and back of the wing and causes the main air stream to break away, with a serious increase in drag and loss of lift. If the wing and fuselage are joined by an expanding "fillet", so arranged that the air stream does not have to expand into any unexpected pockets, the flow will remain smooth and the low drag of both wing and fuselage is retained.

Good streamlining is not always visible to the eye. Take for example the two streamlined forms in the sketch on the next page. The thick short one actually has less drag than the long thin one. This is because drag is formed of two parts, one of which is called "form drag" and depends on the shape of the object, and the other is called "skin friction" and is dependent

Corners must have fillets



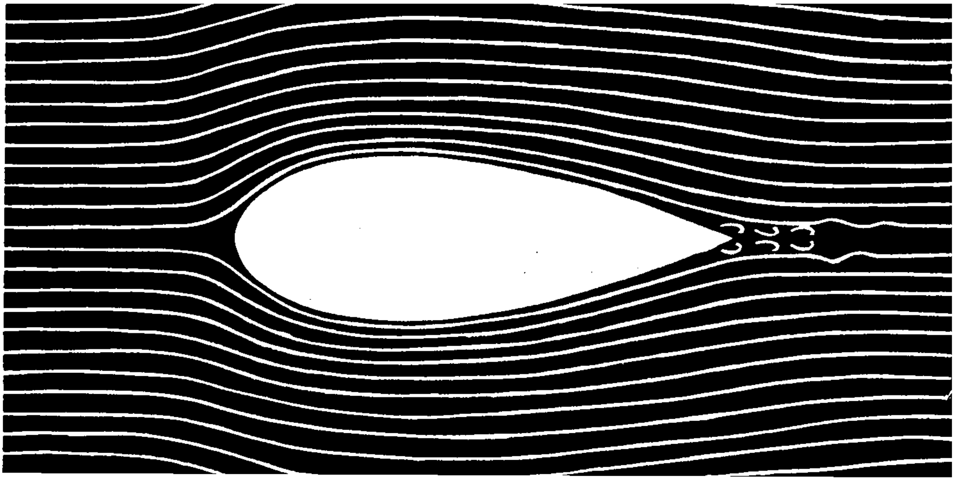
upon the amount of rubbing surface exposed to the air. In these two streamlines the "form drag" is extremely low and there is very little difference between the two. The long thin object has the greater surface, and hence the greater "skin friction", with the result that it has the greater total drag.

Form drag can be greatly influenced by minor disturbances such as a cannon or a landing light, as on the wings of the airplane at the right. These disturbances sometimes have "trigger" effects in that the small disturbance sets off a much larger disturbance in its wake, and the increase in drag is out of all proportion to the size of the object. This characteristic explains why the minor "cleaning up" of an airplane will sometimes result in large gains in speed and at other times, when no trigger effect is present, will have scarcely any result at all.

The illustration at the right also shows three of the most frequent major drag disturbances in addition to an inadequate wing fillet—the sharp corners around the front of the windshield, the external air scoop, and the disturbances at the leading edge of the wing. All may have large trigger effects; some may seriously affect the tail control, particularly when landing or stalling.

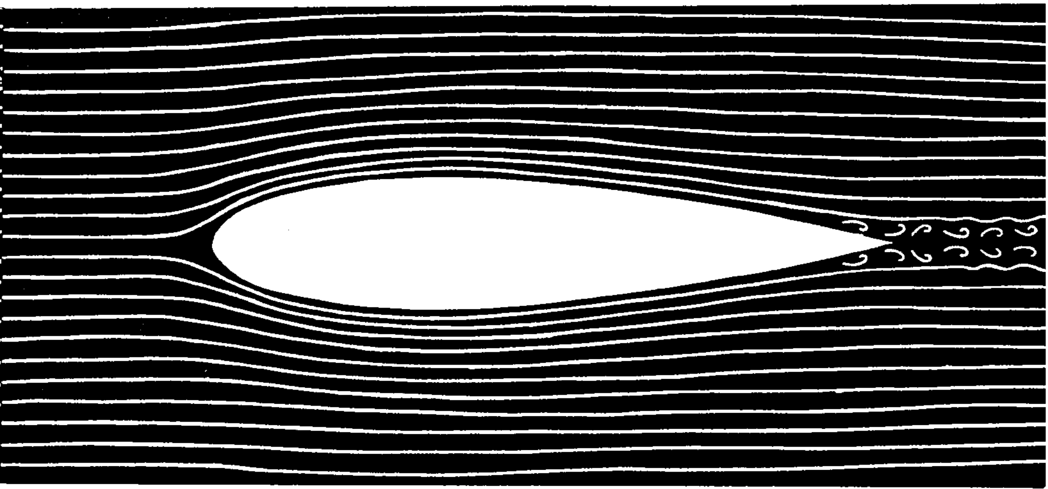
It takes an educated eye to recognize good streamlining.

The short, fat body may have



Good streamlining is not always visible

less drag than the long, thin one



C. TERMINAL SPEED

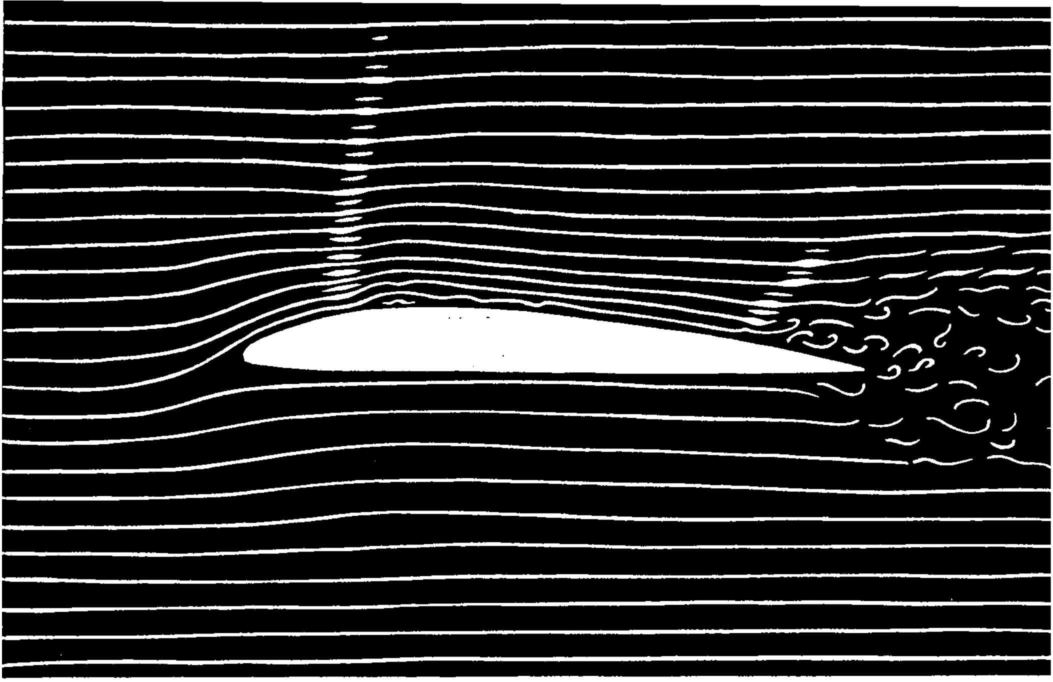
The practical maximum speed of an ordinary object through the air appears to be the speed of sound, which is some 750 miles per hour. Sound, as we hear it, consists of a succession of pressure waves travelling through the air. The speed of sound is defined as the velocity with which the pressure waves travel. If an object attempts to move faster than the speed of sound, the pressure wave generated at its forward point cannot move ahead of the object. It literally cannot get out of the way and must be carried bodily along by the power of the moving object.

A certain rough similarity exists in the bow wave of a steamship. Water which cannot get out of the way is thrown upward from the surface. In the air, however, there is no surface, and no place for the bow wave to go. Hence, it must be dragged along by brute force.

When an object reaches the speed of sound, these effects produce an enormous and sudden increase in drag. The air fails to follow normal laws and will no longer close in behind an object. Under these conditions, no advantage is achieved by streamlining the back of an object. Bullets, for example, need no streamline tails.

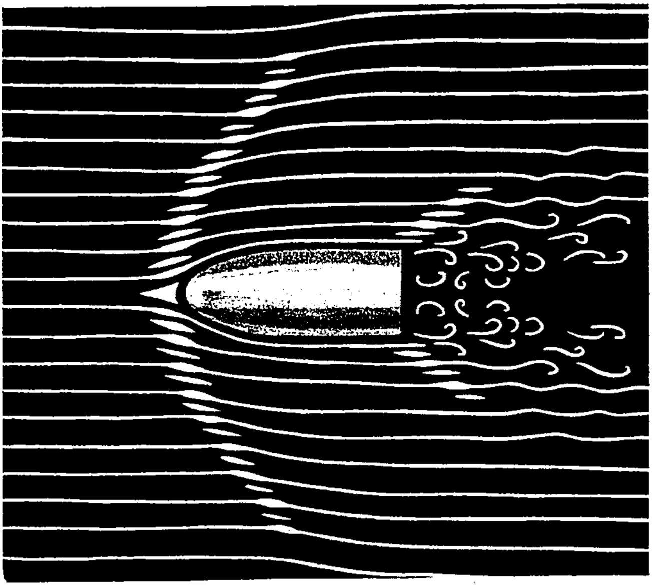
In the case of wings, and also in the case of propellers, the air which flows around the convex side must travel a greater distance, and therefore travel at a greater speed than the air which flows past the flat surface. Therefore, although the average speed of the air flowing past a propeller tip may be well below the speed of sound, that portion of it which flows around the convex surface may be above the speed of sound. The same pressure disturbances then arise as in the case of a bullet.

Photographs of bullets and of wing models have both been made by a special technique and the pressure waves caused by the supersonic flow have been visualized in both cases. The character of these waves is not yet clearly understood. The



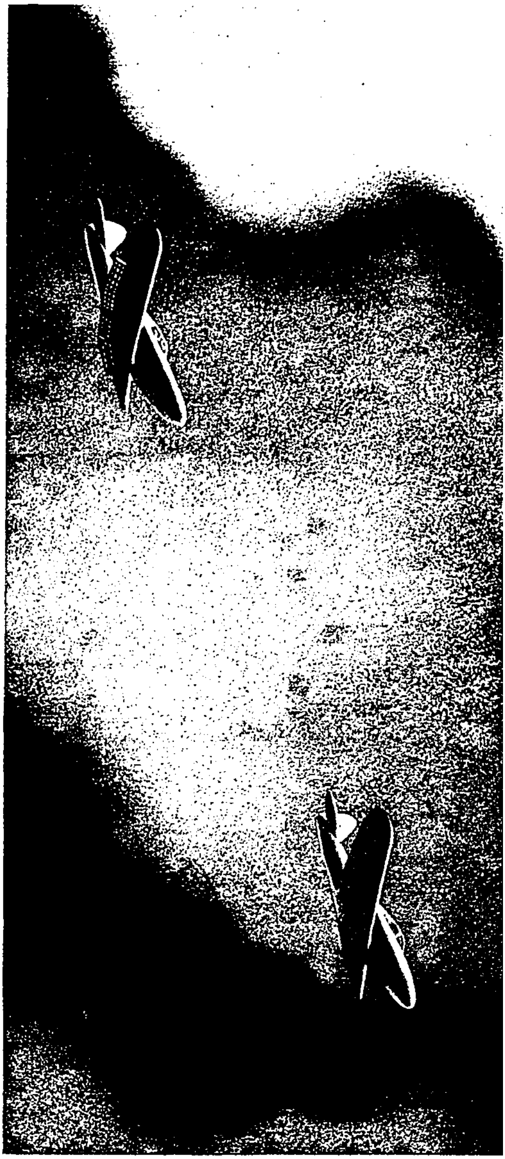
Propellers may have "shock waves"

Bullets don't need tails



accompanying sketches give a reasonably accurate pattern of the pressure or "shock" waves around a bullet and a propeller blade section.

This complex pressure wave phenomena, which is usually called the "compressibility effect" is what gives rise to the unusually loud roar, or whine, of propellers whose tip speed approaches the speed of sound. It also explains why two airplanes may have equal top speeds, yet one may dive much faster than the other. The slow diving airplane has developed a compressibility effect on some part of its structure which has enormously increased its drag. It has reached its terminal speed.


Clean airplanes may need brakes

Experience with slow diving airplanes, subject to large compressibility effects, has demonstrated that the accuracy of dive bombing has been considerably increased by the slow diving speed. Thus it has been found desirable to bring about slow dives artificially by the use of "dive brakes", which may be extended from the wing. Such brakes do not necessarily produce a "compressibility effect", but they do result in large increases in drag and a consequent reduction in diving speeds.

D. STREAMLINING THE INSIDE

Not all of the streamlining is on the outside of the airplane. A large amount of the drag may be caused by the internal airflow through the engine, the radiators, the oil cooler, and the intercoolers. The amount of drag caused by this internal flow depends upon how much air must pass through the airplane and how fast that air is moving.

The air which passes through the airplane is slowed down by the resistance of the engine cooling fins or the radiator, unless some form of blower is used. The loss in speed of the cooling air is thus a measure of the internal drag of the airplane.

Additional drag occurs if more air is passed through the engine or radiator than is required. This may be extremely large unless regulated. The familiar cowl flaps are employed to provide this regulation. If the cowl flaps are opened too far, incidentally, beyond about 25 degrees, no further improvement in cooling will occur, while the drag of the entire airplane may be drastically increased.

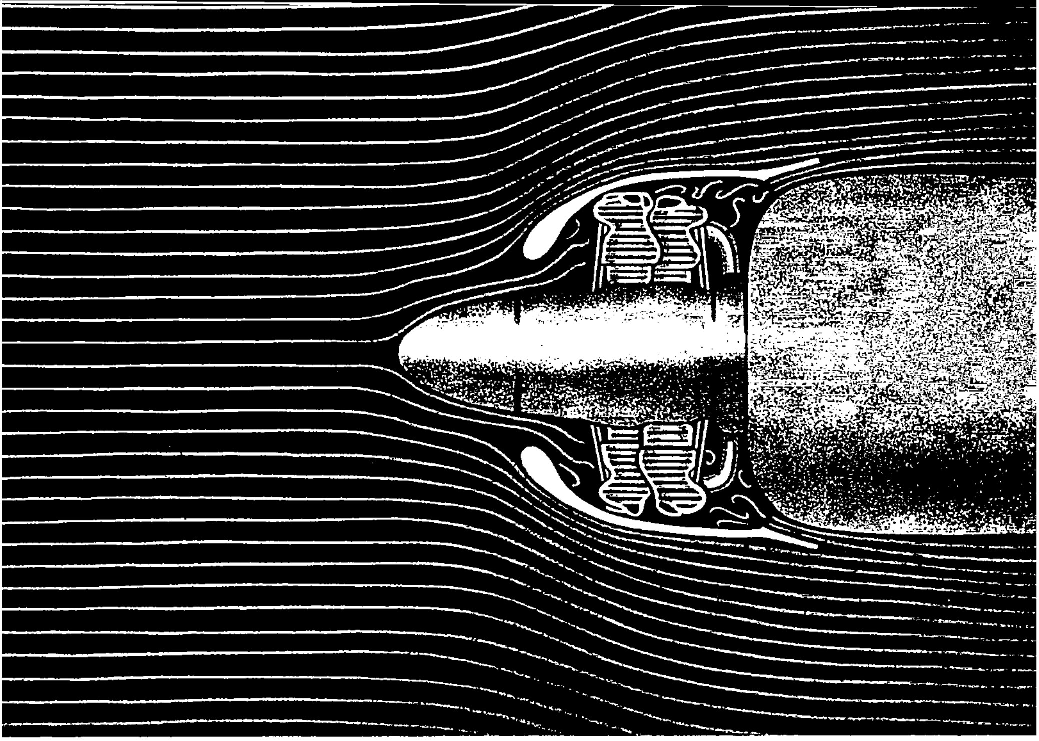
It is theoretically possible to obtain a thrust, or negative drag, from the cooling air. This is the so-called Meredith effect. If the air which enters the airplane is expanded (that is, slowed down so that its pressure rises), and is heated before being allowed to speed up again, it will leave the airplane at a faster speed than when it entered. This is because the heated air which leaves is less dense and occupies more space than the cool air which entered. There is, in effect, more of it, so it must move out faster. Speeding up the discharged air gives a forward thrust, after the manner of a sky-rocket.

Negative drag can only be obtained if the heating device has very low resistance. The beneficial tendency, however, is always present and prevents the cooling drag from being worse than it otherwise would be. To get the greatest benefit from the Meredith effect, the airplane should be fast, the engine (or radiator) very hot and of low resistance.

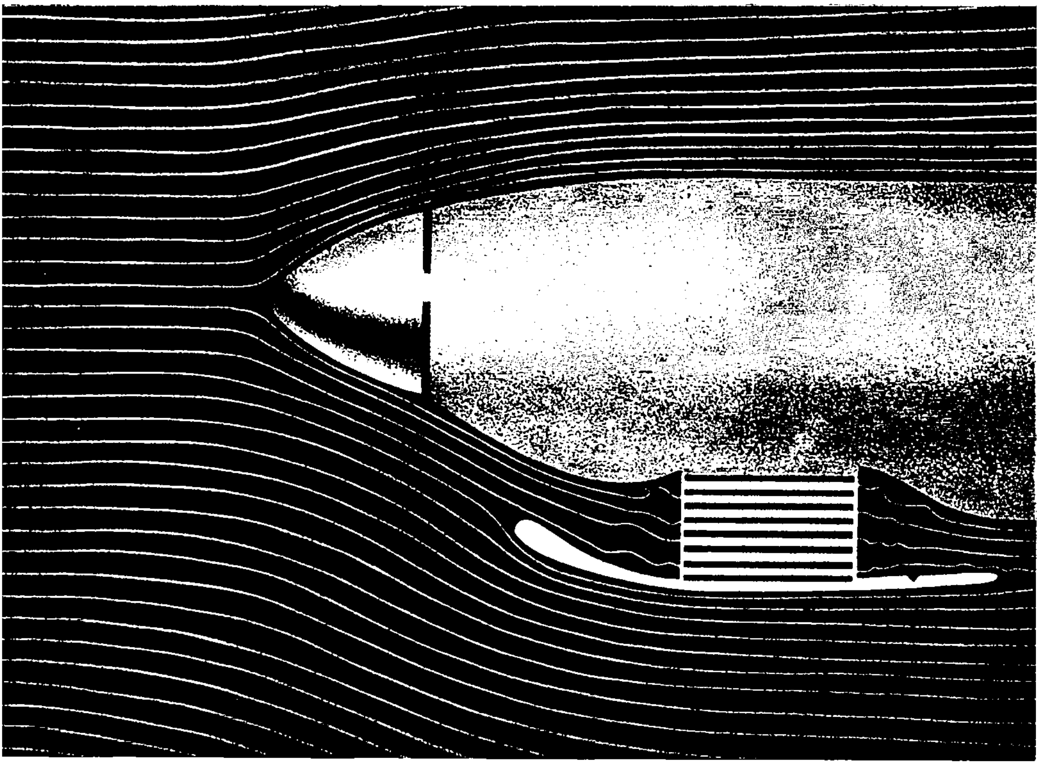
A comparison of the air-cooled and liquid-cooled engine installations in the two sketches is interesting. Since the air-cooled cylinders are hotter than the liquid-cooled radiator, they have less trouble getting rid of their heat and consequently the air-cooled engine tends to require less air than the liquid-cooled radiator. On the other hand, the flow through the cylinder fins of the air-cooled engine is much more complicated than the flow through a radiator, with the result that the "pressure drop" through the engine, or the drag per pound of air used, may be greater for the air-cooled engine than for the liquid-cooled radiator. These two factors, the higher temperature of the air-cooled cylinder and the lower drag of the liquid-cooled radiator, tend to offset each other.

The relative drag of air-cooled and liquid-cooled installations depends largely on the skill with which the designer handles the air ducting. Since it is not always handled with the same amount of skill, it is extremely difficult to compare the two types.

At high altitudes, where the ducting problems are not clearly understood, it is not yet possible to determine which will have the lower drag. At low altitudes, however, the difference in drag between the air-cooled and the liquid-cooled installations, per horsepower, is rapidly tending to disappear.



The relative drag of air-cooled and liquid-cooled installations depends more upon the designer's skill in handling the inside streamlining than upon the outside shape

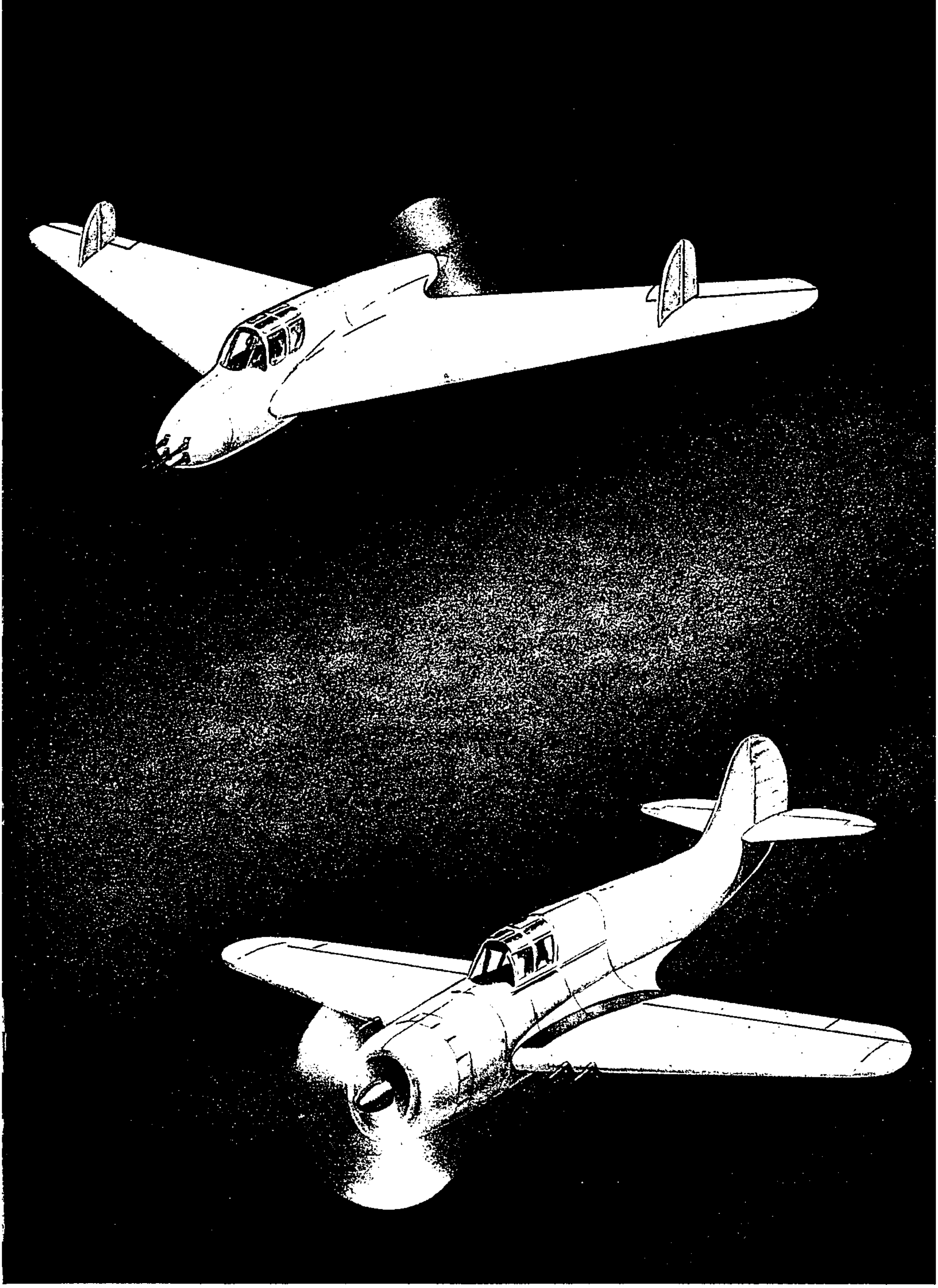


E. THE "FLYING WING"

Several experimental models of the "Flying Wing" type have appeared during the last decade in Germany, England, and the United States. Such airplanes are promising because they eliminate the drag of the fuselage and tail, but they have a number of disadvantages.

The usual conception of a "flying wing" airplane pictures everything housed smoothly within the wing surface. Although this may be possible on a giant airplane having wings 8 or 10 feet thick, it is very difficult in the small fighter types. The amount of equipment and fuel, not to mention the engine and the pilot, which must be carried by a modern pursuit plane is so great that it cannot be contained in a normal wing. Even if a flat engine were developed to fit within the wings, its presence there would displace fuel or guns or equipment. The two usual expedients are to thicken the wings to provide the necessary space or to provide a nacelle to house the pilot and engine. The latter generally, but not always, provides the more economical use of space, and hence the lower drag.

Finally, no way has yet been discovered to permit the "flying wing" type of airplane to employ such effective high lift devices as are used on conventional airplanes. When in use, these devices tend to make the airplane dive, a tendency which is normally offset by the tail. In the case of the "flying wing", the little horizontal flippers at the wing tip serve as both ailerons and elevators (the vertical surfaces, of course, serve as rudders), but they are not so effective as a conventional tail. Consequently the "flying-wing" type must employ a low lift wing and therefore requires more wing area than the conventional type, which somewhat offsets the benefits of its cleanness.



The "Flying Wing" has its problems, too

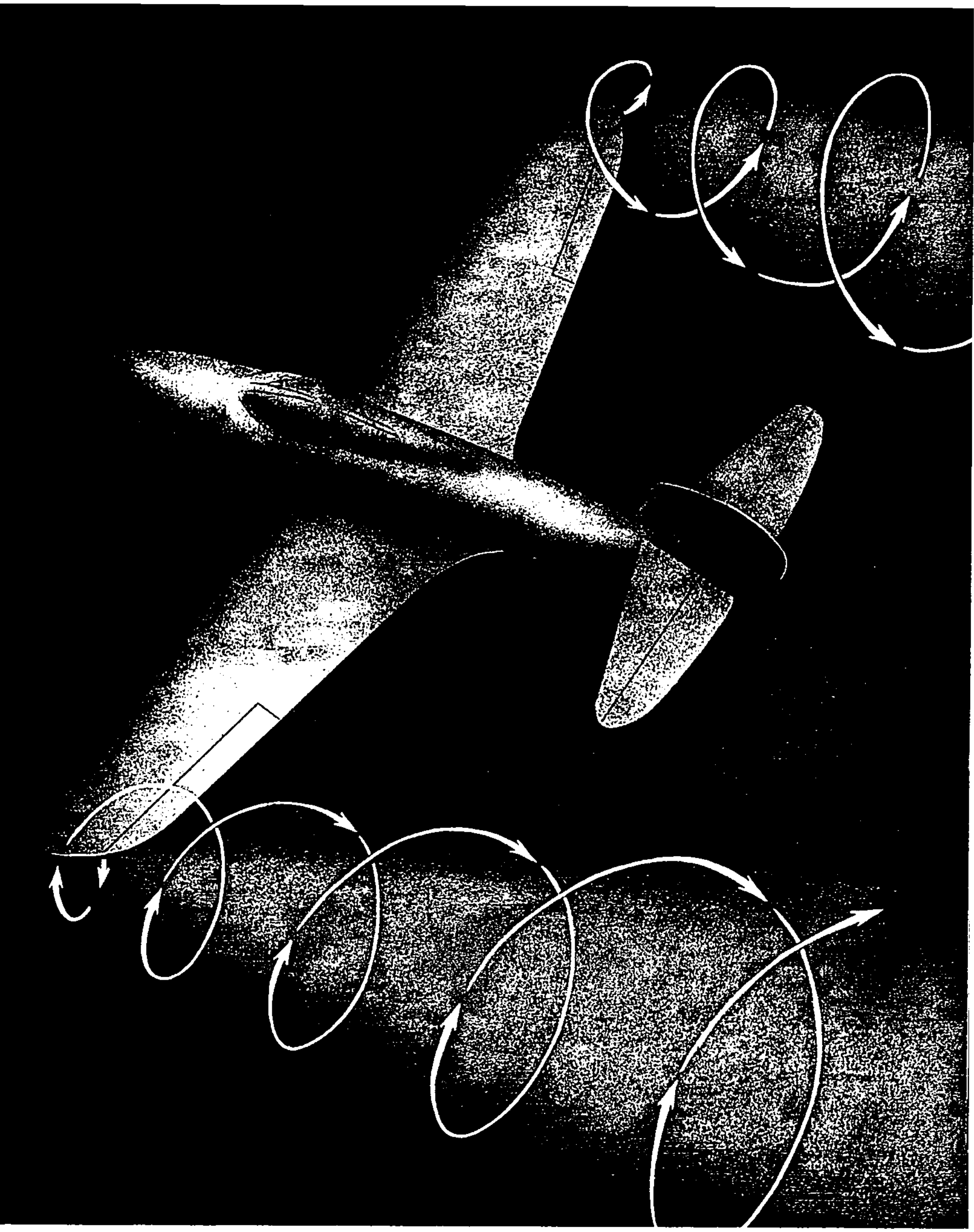
V. THE EFFECT OF SPAN LOADING

A. INDUCED DRAG

In any airplane the air under the wing is at a positive pressure, while the air above the wing is at a negative pressure. At the wing tips the high pressure air under the wing tends to curl upward around the wing tip and flow toward the low pressure air on the upper surface. This results in a pair of trailing vortex patterns shown diagrammatically on the accompanying sketch. It will be noted that throughout the entire region behind and between the wing tips, the air tends to flow downward, whereas beyond the wing tips it tends to flow upward. Thus, the airplane itself is flying in a region of down-moving air or "downwash". This condition of flying level in a downwash is really the equivalent of climbing, or "flying uphill" in still air. Put another way, it is the equivalent of flying level with an increased drag. In fact, it is customery for engineers to think of the *drag* induced by the wing tip vortices rather than to think of the angle of downwash, or the corresponding angle of climb, which they produce.

The magnitude of these tip vortices depends upon four things. First, the heavier the airplane, the more violently will it deflect the air downward in order to support itself, and the greater will be the tip vortices and the downwash which they create. Second, the farther apart the wing tips are, the greater will be the mass of air on which the wings can act, and the less it will be deflected downward, and hence the smaller will be the effect. Based on these two factors it is desirable to have the weight small and the span large. The actual basis on which these effects are calculated is the "span loading", which is the gross weight divided by the wing span. The lower this loading, the smaller the induced drag.

The third element affecting the downwash and the induced



The air curls up around the wing-tips and makes the airplane fly uphill drag is the speed of the airplane. If the airplane is flying very fast its wings work upon a large mass of air per second. The larger this mass, the less it need be deflected downward to support the weight of a given airplane. If the air is not deflected down so much, the tip vortices are less violent and the induced drag is less. Thus, induced drag, unlike any other kind of drag, gets less as the speed increases. At high speed this drag is usually but a small proportion of the whole and changes in it become relatively unimportant, but at climbing speed or cruising speed it is the major drag element.

The fourth effect is caused by the change in air density as the altitude is increased. Since the density at 40,000 feet is but one-fourth that at sea level, the wing acts on only one-fourth the mass of air, and consequently must deflect it downward four times as much. This results in the induced drag being roughly four times as great at 40,000 feet as at sea level. For this reason it is extremely important that high-altitude fighters have large wing spans, whereas low-altitude fighters may have small spans since the effect at low altitude is negligible.

Likewise, it is important that long-range airplanes should have large spans, because the most economical cruising speed is much slower than the top speed, and at these slower speeds the induced drag is large, as explained above. At cruising or climbing speeds, the induced drag may amount to more than half the total drag of the airplane.

VI. PROPELLER EFFECTS

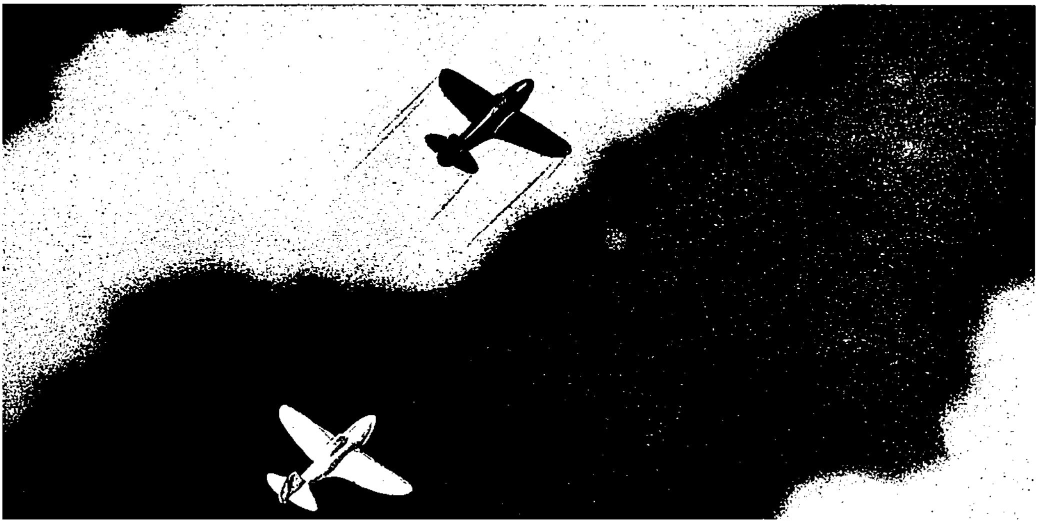
A. PROPELLER LIMITATIONS

There is scarcely any part of an airplane whose improvement will pay a bigger bonus than will the airplane propeller. Increased propeller efficiency is power without weight. This means improved takeoff, improved climb, improved ceiling, improved range, and improved speed.

The modern propeller is already an extremely efficient device, so that further improvement is far from easy. More than 86% of the power delivered by the engine can be transmitted into useful thrust by the propeller under optimum conditions. Unfortunately optimum conditions are usually difficult to obtain, due to limitations in the permissible size of the propeller and other factors. However, the efficiency can be improved at slow speeds by sacrificing the efficiency at high speeds, or vice versa. This results either in improved takeoff and climb, or in improved top speed, one at the expense of the other.

The propeller obtains its thrust by pushing air backward, just as a wing attains its lift by pushing air downward. The amount of thrust is dependent not only on the speed and size of the propeller, but also on the angle of the blades to the relative wind. If this angle is too small, the propeller will not

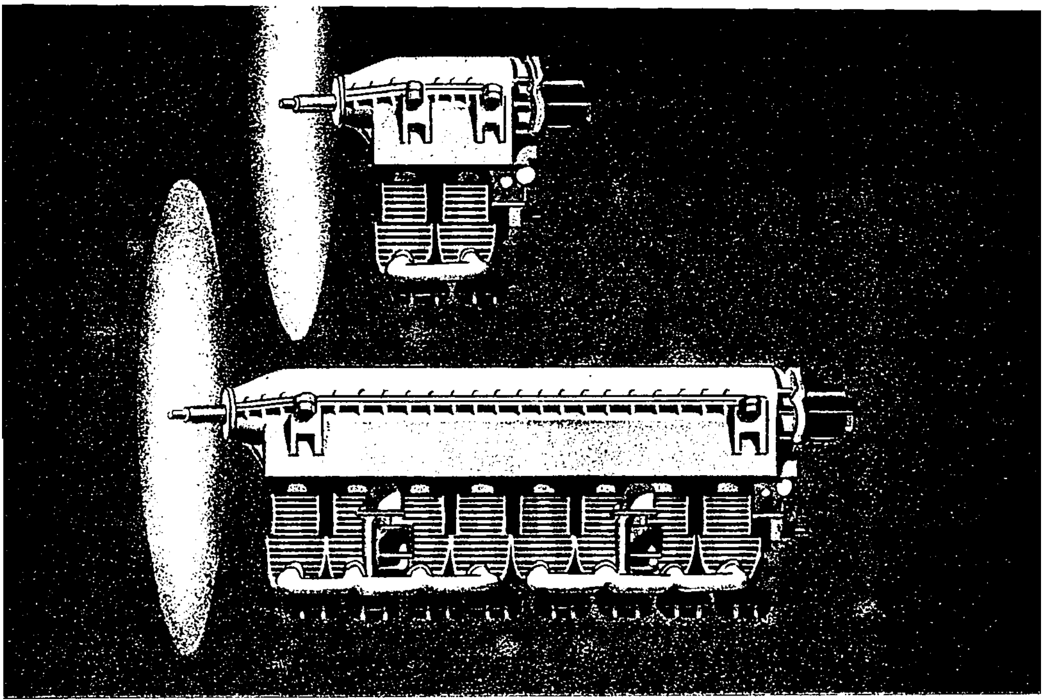
Increased efficiency is power without weight



produce as much thrust as the engine has power to create, so the engine will race. For this reason the "constant speed" propellers have been designed wherein the angle of the blades is automatically controlled by a governor attached to the engine. By this means any desired engine speed or power can be maintained, irrespective of the speed of the airplane or the altitude at which it flies. The use of constant speed propellers is essential to all high performance aircraft.

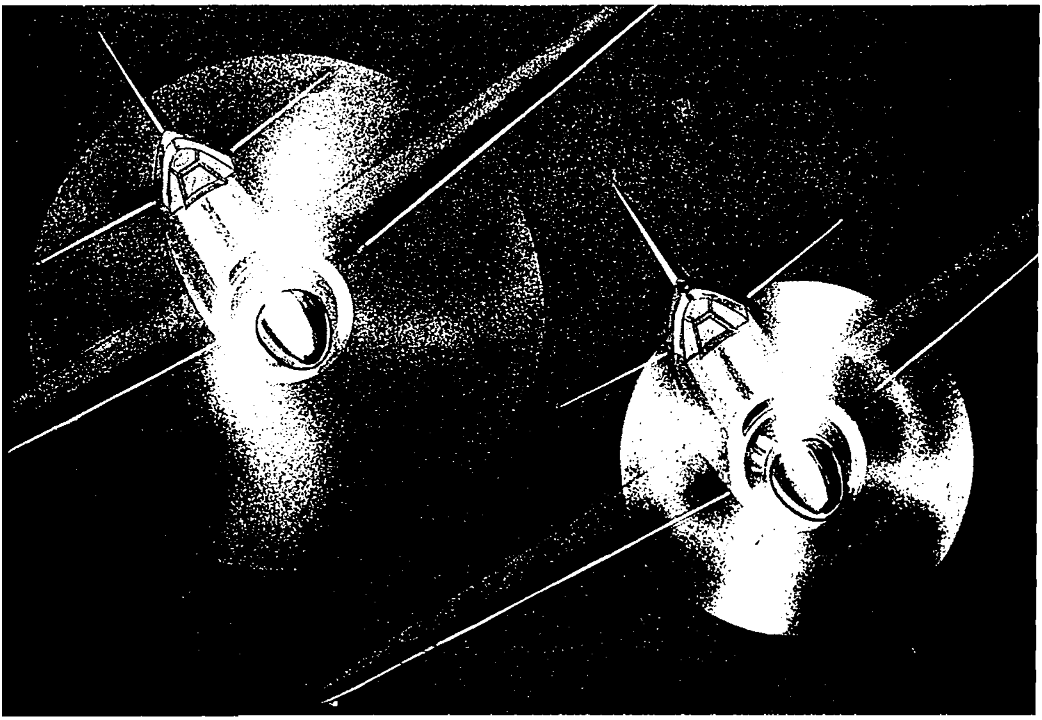
Some idea of the difficulties of propeller design may be appreciated when one realizes that the air density at 40,000 feet is one-fourth that at sea level. At any given speed, a propeller big enough to absorb 2000 horsepower at 40,000 feet will be big enough to absorb 8000 horsepower at sea level. Even with the maximum adjustment of propeller blades, it is not possible for a propeller to be efficient under both these extreme conditions.

Another limit which always confronts the aircraft designer is that the propeller tips cannot move with a velocity in excess of the speed of sound without producing the large drag effects and the excessive noise mentioned previously under "Terminal Speed", with a corresponding loss in efficiency. Since the speed of a propeller tip is proportional to its diameter and its revolutions per minute, it follows that the bigger the propeller, the slower it must turn. However, the slower turning propeller will not absorb as much power as a fast turning propeller of the same size, and consequently it becomes progressively more difficult to design propellers for very powerful engines, particularly at high altitudes.



A propeller big enough to hold 2000 H.P. at 40,000 ft. will hold 8000 H.P. at sea level

The bigger the "prop" the slower it must turn



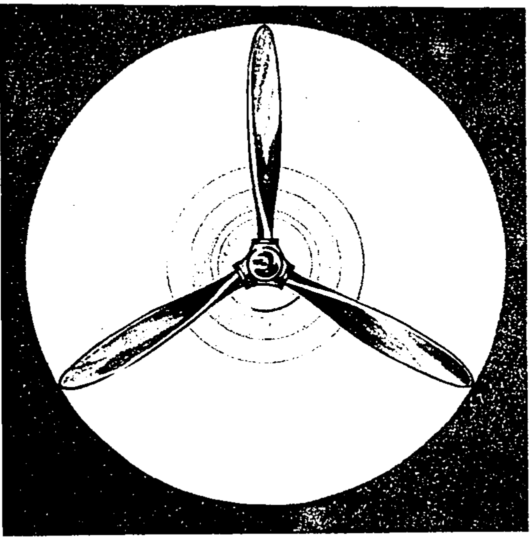
B. METHODS OF ABSORBING POWER

Since the speed of sound limits the permissible tip velocity of a propeller, it is often suggested that high powered propellers should have more blades. This has been done experimentally several times, but it is very difficult to design a single hub which will hold the extremely complex loads from several highly loaded propeller blades. Also, certain severe vibration conditions are frequently encountered when more than three blades are employed, and this adds greatly to the engineering problems.

One method of avoiding these difficulties is to mount two propellers, one behind the other, rotating in opposite directions. Dual-rotation propellers of this sort have also been built experimentally. They have the added advantage of having no torque reaction. Thus, when the throttle is opened or closed suddenly, the airplane has no tendency to roll. Such propellers require relatively heavy and complicated gearing in the engine, but under certain circumstances the advantages are great.

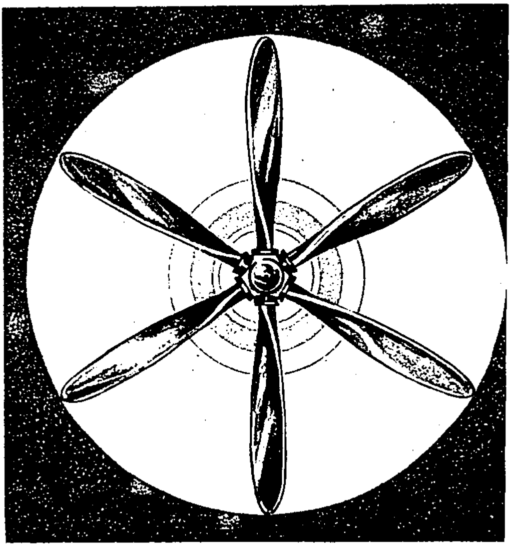
Perhaps the simplest solution is to make wider propeller blades. Such blades tend to be heavy; however, they have the property of improving the flow of air past the engine hub, and thereby improving the engine cooling. Occasionally "cuffs" of some light material are employed to provide greater blade width near the hub for cooling purposes.

For every combination of airplane, engine, and propeller there is an optimum speed of rotation for the propeller. The maximum power of the engine, however, is always obtained at the same engine speed. Hence, the reduction gear in the nose of the engine which determines the propeller speed must be different for every airplane and for every propeller. If this were actually done the production problems in the engine factory as well as the supply problems in the military services would become hopelessly complicated. It has become necessary to standardize on a few specific gear ratios, and utilize these for

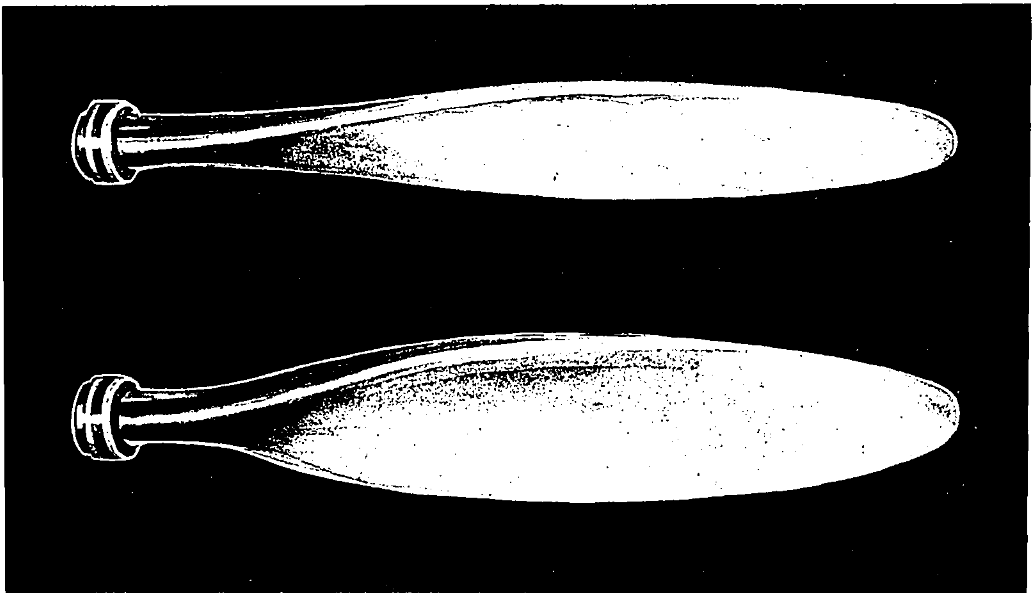


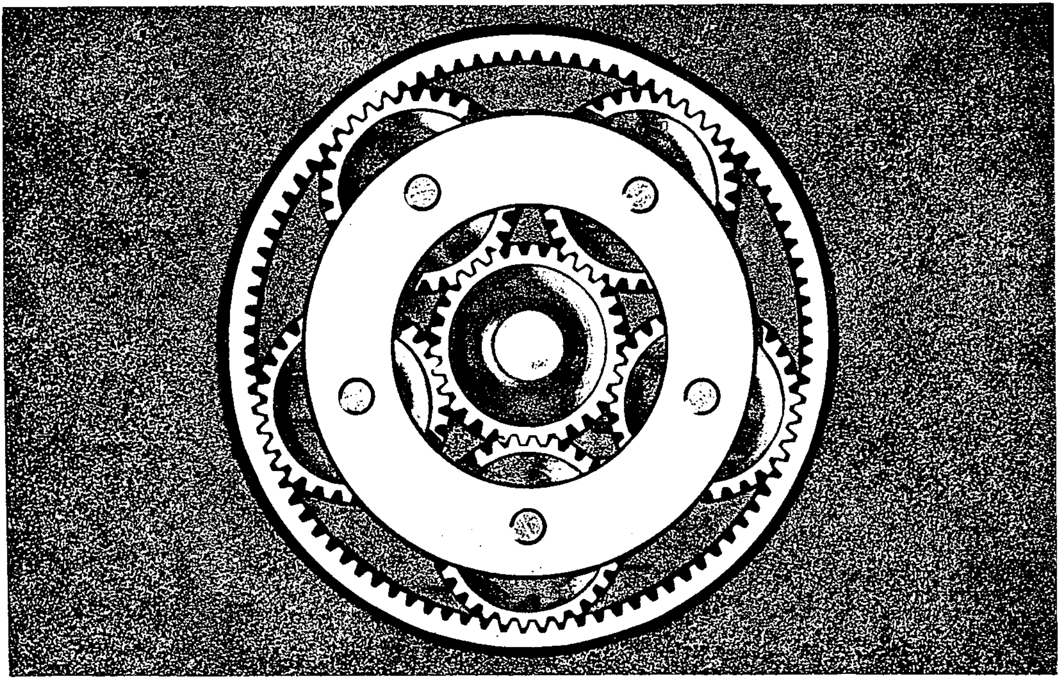
More power . . .

. . . requires more blades



. . . or wider blades





The gear ratio is always a compromise

all airplanes and propellers. The inevitable result is a compromise in performance, which is occasionally severe.

In certain high performance airplanes the optimum propeller gearing differs so greatly between high speed and takeoff that two different gear sets with a gear shift lever have been seriously proposed. This emphasizes again the importance of having the correct propeller speed for any given installation. In view of the importance of these propeller effects, one must be extremely careful in making comparisons between different types of engines in the same airplane.

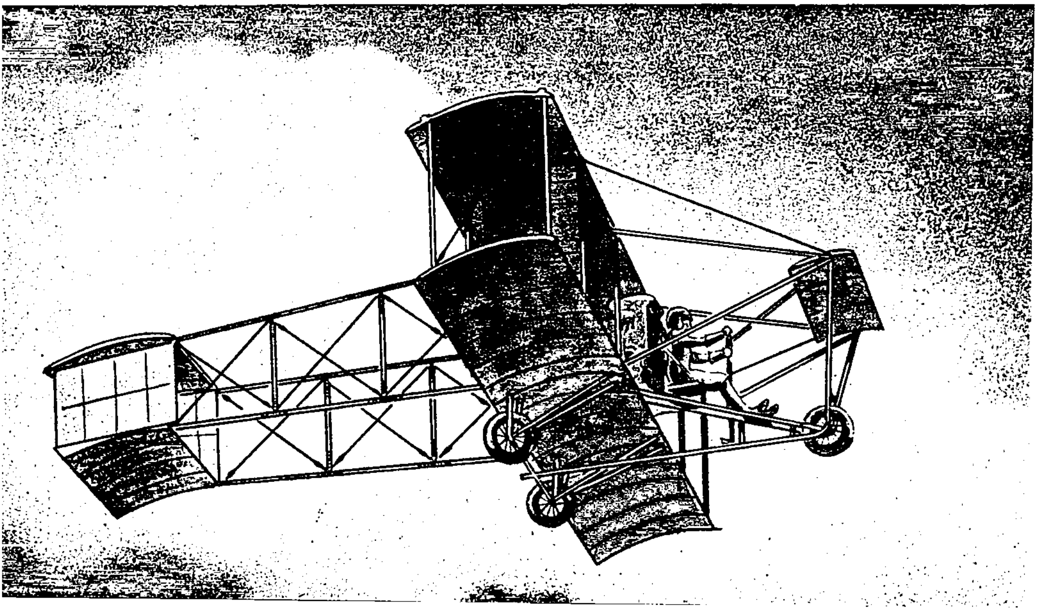
VII. SUMMARY

THE BEST FIGHTER

There is no "best" fighter airplane. The individual circumstances always govern the need. With no opposition, almost any "crate" will win the war. When conditions change rapidly, the versatile fighter is the best fighter. It need not exceed in any single respect, but if it is a good "Jack-of-All-Trades" it is the most useful airplane which can be had. However, if the competition is close and the opponent well organized, then the specialist will win.

Take the low altitude fighter, with high wing loading and heavy fire-power, for example. It can overtake, outrun, and outgun the "Jack-of-All-Trades." The same specializing can be done at altitude. The supercharged fighter with high wing loading will specialize in speed at altitude; the supercharged fighter with low wing loading will specialize in climb and maneuverability. Further specialization is required in the night-fighter and frequently for the long-range types. However, any fighter can be converted to a long-range fighter by the use of auxiliary disposable fuel tanks and other expedients.

Any "crate" will win . . . . . . if there is no opposition



SUMMARY

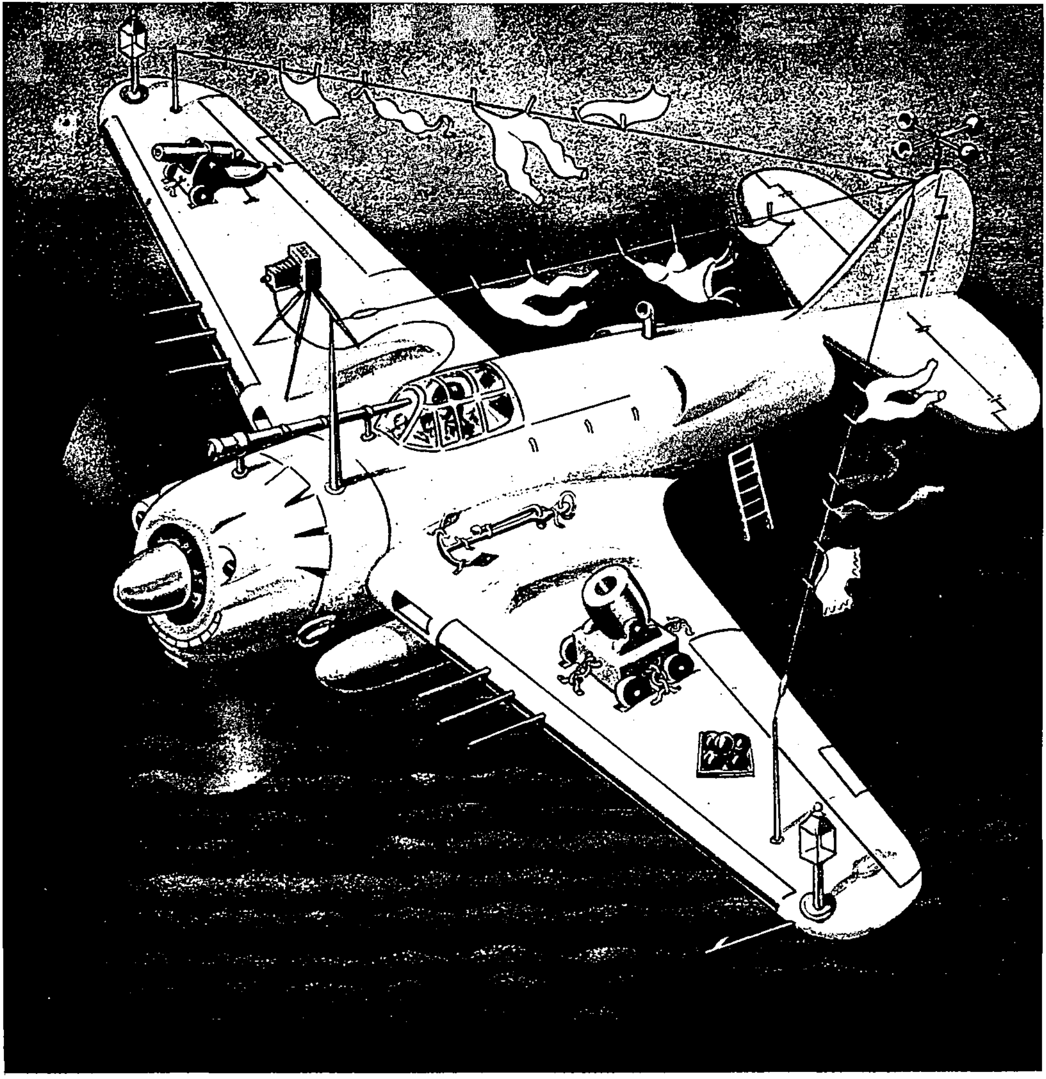
It should not be assumed that the "Jack-of-All-Trades" type will become obsolete, nor that it will retain any fixed forms. Certain dual-purpose types, such as the fighter-bomber have already made their appearance. The bomb is carried on the outside. The weight and drag of the bomb—even the drag of the empty bomb racks with their appropriate braces—will definitely harm the performance of the airplane. If the airplane is revised to house the bomb on the inside, a major redesign is involved, with the certain result that the final airplane will have a poorer performance than the original fighter.

Whether such dual-purpose airplanes should be built cannot be determined from engineering studies alone. It is a matter of expediency. It depends on the military action which is contemplated, upon the equipment of the enemy, upon what models are in production that may be converted to new uses. The essential point is that compromise is involved. If an airplane must undertake two tasks, it will not be as good at either as if it were designed for one alone.

There is an important corollary to this argument. If we specialize, we must specialize in *all* types including the "Jack-of-All-Trades" type. Specialization in one feature inherently makes an airplane poorer in all others. If we specialize exclusively in high altitude fighters, we lay ourselves open to the enemy who specializes in low altitude types and persistently avoids fighting at high altitudes.

Any airplane is a compromise, and as with all compromises, no definite rules can be laid down. No single solution is the right answer. However, some measure of the gains to be made from certain design features and the sacrifices which are entailed may be useful. The table, on pages 62-63, which may be considered typical of modern fighters but which cannot be precise for any one fighter, gives some concrete evaluation to the facts we have been discussing.

In conclusion, it is the procurement officer's problem to ob-



Jack-of-all-trades, or master of one?

tain a fighter airplane, the tactician's problem to employ it, and the pilot's problem to fly it. The task of each is made easier by an understanding of the engineering background of the airplane itself. In supplying a part of this background, it is hoped that the present discussion has been helpful.

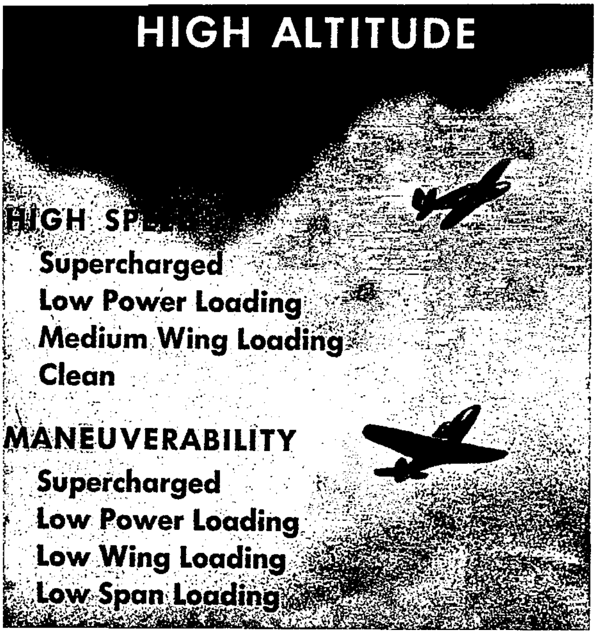
FACTORS AFFECTING PERFORMANCE

A 10% reduction in the items in the left hand column

	TOP SPEED	*CLIMB AT SEA LEVEL*	*SERVICE CEILING*
Wing Loading (Note 1)	−2%	− 1%	+1%
Power Loading	+3%	+13%	+3%
Span Loading (Note 6)	0	+ 2%	+3%
Critical Altitude	(Note 2)	0	−4%
Drag	+3%	+ 1%	+1%
Gross Weight	+1%	+14%	+4%

1. The wing area was changed while holding the ratio of span to chord constant. This has the effect of making a 10% reduction in wing loading and a 5% reduction in span loading simultaneously.
2. A 10% reduction in critical altitude results in the airplane being some 2% slower at the lower altitude than it was at at the higher. However, if the comparison is made at the higher altitude, the airplane will be some 7% slower at that altitude than previously.
3. Nominally, a reduction in power loading does not affect the range. Actually, an increase in power improves the take-off so that the airplane can get off with an overload of fuel, thus adding substantially to its range.

An increase (+) in top speed, climb, ceiling, and range is desired



HIGH ALTITUDE

HIGH SPEED
- Supercharged
- Low Power Loading
- Medium Wing Loading
- Clean

MANEUVERABILITY
- Supercharged
- Low Power Loading
- Low Wing Loading
- Low Span Loading

LONG RANGE
- High Take-off Power
- Large Tanks
- Large Span
- Clean

OF A TYPICAL FIGHTER AIRPLANE

will affect the performance approximately as shown.

TAKE-OFF RUN	LANDING SPEED	RANGE	TURNING RADIUS
– 9%	– 5%	+ 1%	–10%
– 5%	0	(Note 3)	(Note 4)
0	0	+ 3%	(Note 4)
0	0	0	0
0	0	+ 5%	(Note 4)
–13%	– 5%	(Note 5)	–10%

4. Under certain circumstances the drag of an airplane is so great in a turn that the engine does not have sufficient power to pull it around as tight a turn as it would otherwise make. In these instances an increase in power or in wing span (decrease in power loading and span loading), or a reduction of drag, will all serve to reduce the turning radius.

5. If the increase in gross weight is all in fuel, the range will increase roughly in proportion to the fuel added. If the weight is not in fuel, a slight reduction in range will result.

6. A reduction in wing loading, power loading, or span loading in this table is equivalent to an increase in area, power, or span.

A decrease (—) in take-off run, landing speed, or turning radius is desired